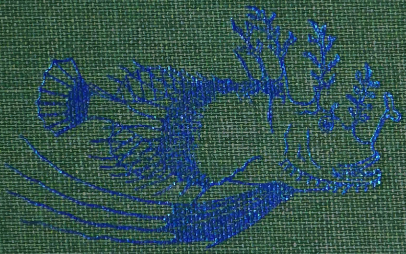

Harvest of the Sea

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Harvest of the Sea

JOHN BARDACH

TO FINA, GOOD COMPANION

AND FISH COOK PAR EXCELLENCE

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Harvest of the Sea

The farmer has his rent to pay.
Haul, you joskins, haul.
And seed to buy, I've heard him say.
Haul, you joskins, haul.
But we who plow the North Sea deep
Though never sowing, always reap,
The harvest which to all is free,
And Gorleston Light is home for me,
Haul, you joskins, haul.

—"Yarmouth Sea Chantey"

Introduction: Beginnings

Nearly a century ago a steam-driven corvette, H.M.S. *Challenger,* set out from Plymouth for the first oceanographic cruise worthy of the name. Her 70,000-mile journey, which took soundings and samples in all the world's oceans, became the subject of the *Challenger Reports,* thirty-two volumes that included descriptions of many new species and that have aptly been called the Bible of Oceanography.

Our knowledge of the oceans, though still very incomplete, has grown by leaps and bounds since *Challenger*'s return to port. We now view the sea as a dynamic system that has interplay with the atmosphere above as well as with the earth's crust below. Her tides ebb and swell in the estuaries of our rivers. These in turn drain the land, carrying salts, silt, and (after heavy rains) precious soil down to the sea. Evaporation from the sea is the source of most of the rain that falls on the land, and the water that flows downstream as a result is but one link in the all-important cycle that transports water molecules—to state the process as simply as possible—from ocean to clouds to rain or snow to soil to lake or river and then back into the sea.

The oceans, the source of rain and the mainspring of weather, cover 70.8 percent of the surface of the globe. Under their restless, almost transparent surface lie the earth's deepest valleys, as well as vast mountain chains, plains, abrupt canyons, and possibly greater and fiercer volcanoes than can be

found anywhere on land. If we do not include in our measurement of the water surface the so-called mediterranean and marginal seas, or such smaller basins in the midst of land as the Black and Caspian Seas, or Hudson Bay, or the North Sea, but only look at the biggest oceans, namely the Atlantic, the Pacific, the Indian, the Arctic, and the Southern Oceans, the water-covered surface of the globe shrinks to just under 64 percent. The smaller seas are also shallower than the big ocean basins, and if they are included in the calculation, the average depth of the oceans comes to only 3,795 meters* (12,448 feet) as opposed to 4,117 meters (13,504 feet) if we considered none but the major basins, mentioned above. Of greatest interest to us now, because we are about to conquer them, are areas far shallower than the ocean's average depth. The continental shelves extend from the land masses like steps at the edge of what may be called the twilight zone. On an average they are 200 meters (656 feet) deep, and beyond them the slope drops off into the perpetual darkness below. Whether or not the various mediterranean seas are included in the calculations, the total area of the continental shelves is at least three times larger than that of the entire United States.

Shelves and mediterranean seas seem permanent enough when compared with the life span of man, or even with his total recorded history. Yet geologic evidence shows that parts of the shelf were exposed several times during the last ice age, which lasted a million years; the sea then was from 200 to 300 meters (or from 656 to 984 feet) shallower than it is today. Still more ancient fossil traces indicate that vast shallow seas covered much of the present continental area about 300 million years ago. It is clear that continents rise and fall; one need not

* The reader is reminded that of the systems of measurement in use throughout the world the metric system is the one adopted by science. Since navigation is an old craft and antedates the formulation of the metric system, sea depths, distances, and movement on her surface are measured in many different units—knots, nautical miles, fathoms, feet, etc.

even adduce as evidence the haunting tales of lost continents to understand that many regions now submerged must once have projected above the water.

As compared with the barely perceptible rising and sinking of the ocean bed, the motion of the water masses above it is rapid. Driven by the wind and deflected by the earth's rotation, surface currents transport truly gigantic amounts of water across the seas: the Florida Current, which farther along its course becomes the Gulf Stream—to name only the best known of many such currents—pushes 26,000 tons of water per second past Miami and flows at a surface speed of about three miles an hour. Inasmuch as surface currents naturally pile up water in some areas and remove it from others, there are not only surface countercurrents and upwellings of deeper waters that replace what was removed but also vast movements of intermediate and deep water masses, often flowing for thousands of miles—such as the water that originates near the zone of permanent ice in the Antarctic but can be traced all the way to the North Atlantic. Although ocean currents and upwellings are responsible for the distribution of nutrients in time and place, and consequently for the abundance of life in the sea, the sunlight that strikes the surface and penetrates a short distance below it is still the prime force that makes the oceans teem with life.

The sunlit surface layer, or photic zone, is but a film, albeit an important one in proportion to the depth of waters beneath it. In the top 100-meter layer (328 feet), if the ocean water is clear, the chlorophyll and other pigments of algae absorb the sun's energy and cells take in dissolved nutrients. Thus begins the complex chain of dependencies by one organism upon another that extends down to the very abyss, for life has been discovered even in the deepest ocean trenches.

The oceans differ in transparency; in the clearest sea, for instance—the Southern Indian Ocean—delicate instruments

can still detect traces of light below 1,000 meters (3,280 feet). But in most seas the underwater world becomes black at much shallower depths; even at 40 meters (131 feet), which is the limit of most aqualung diving, the light is greatly cut down and seems to come from all directions. Close to the shore and in the harbors and estuaries the water is less transparent still, so that a few meters, perhaps barely a dozen feet, is often the limit of visibility and thus of photosynthesis.

Those who have used aqualungs or other self-contained underwater breathing apparatus—a phrase generally abbreviated as SCUBA—now tend to take the equipment for granted, forgetting that first the air and then the undersea environment were both invaded only in this century. Until about 1950 almost all samples of the bottom or of plants and animals, even in shallow waters, were obtained only by lowering suitable instruments here and there. Oceanographic data-taking—whether physical, chemical, or biological—was like flying over a landscape in a fog and lowering a net, a rake, and a thermometer to the ground. Any reconstruction of what the area was like would be like basing such knowledge of dry land on a few blades of grass with sand grains clinging to them, the twig of a shrub or a tree, a few insects, and a mouse that, with good luck, might have been collected. After the second decade of the twentieth century, with the invention of the echo sounder, the fog was lifted a bit, so far as subsurface topography was concerned. Sound beams reflected from the ocean floor permitted a graph profile of the seascape to be made. Yet the ocean is so vast that at present there do not exist detailed charts even for all inshore areas, to say nothing of the deep ocean basins.

Today not only SCUBA, of which the aqualung is but a variant, but all sorts of submersibles, such as diving saucers, atomic submarines, and bathyscaphes, have afforded to a few men, at least, a glimpse of some parts of the oceans, from top to bottom.

We can even work in the sea at a depth of about 100 meters (over 300 feet), as American and French diving teams have proved. And going beyond the range which man himself can now enter, mechanical hands attached to submersibles have already been made to do the work for us. The recent raising from 760 meters (about 2,500 feet) of an H-bomb lost in the ocean off the coast of Spain was accomplished in this way. But to continue the comparison between man's invasion of the air and of the sea: in the sky we merely transport men and things a good deal faster than is possible on the ground, but from the ocean, now that the exploration has truly broken through the surface, the rewards promise to be far greater.

Perhaps the greatest importance of the sea lies in the possibility that its inhabitants can supply all-important proteins to the geometrically increasing numbers of people throughout the globe. There is hardly a sea animal that cannot be eaten after proper preparation; yet we utilize but a small number of all species of animals that make their home in the sea. Of the 25,000 or more existing species of fish we capture consistently for food only about 200; of the mollusks, such as clams and oysters, and of the crustaceans, including shrimp, we use proportionally even less.

Fishing today is still the stalking of an invisible quarry. Even on the vast commercial scale practiced by the Japanese and Russians, it amounts simply to the taking of nature's surplus. As yet we can do almost nothing to influence the abundance of most marine animals, and beyond certain limits, animal populations cannot be exploited without depleting them. It has been estimated by some scientists that one can raise the present fish catch in the world perhaps by a factor of two or three before repercussions set in on a global scale. Other estimates are more optimistic. It is also clear that the exploitation of some marine populations, such as the whales and certain fish stocks in the North Sea, has already reached too high a level.

But there are certainly stocks of fish still unexploited, such as

the hakes that abound in the twilight zone of the North Atlantic (Fig. 1). Some may be a bit beyond the reach of our present fishing tools; others may not yet be economical to catch. For it must not be forgotten that fish and other seafood must be sold at a profit, even in Communist countries where the state pays the bill.

Products from the algae, known to most people as seaweeds, are now employed in food processing, cosmetics, plastics, and other industries. Their use is likely to grow, as is that of other special compounds, especially for pharmaceutical use: puffer-fish poison, for instance, yields a potent painkiller; sponges produce antibiotics that attack penicillin-resistant bacteria;

Bingham, U.S. Bureau of Commercial Fisheries

Fig. 1. A hake, relative of cod and whiting, found in vast numbers on the North Atlantic sea bottom. It is utilized for food by the Russians, but not by the United States.

and antivirus drugs are being derived from the body fluids of clams and oysters.

The domestication of land plants, such as rice, wheat, and barley, and of animals, such as horses, cows, sheep, and poultry, was one of the most momentous of human cultural advances. Marine plants and animals have really not yet been subjected to the combination of science and husbandry skills that could now be brought to bear on them. Of late some beginnings have been made—mainly in the Orient, where oysters, shrimp, various kinds of seaweed, and even fish are grown in a manner closely resembling agriculture. These attempts at what may be called aquaculture promise a breakthrough in food production that could push back the specter of hunger from many parts of the world.

It is believed that the continental shelf contains on the average as much mineral wealth per square mile as the dry land; and some of these minerals are now being lifted from the ocean floor. Coal mines lie underwater off Britain and Japan; tin is mined from the drowned beaches of Thailand and Malaya; and diamonds are dredged from the shallows off South Africa. Sulphur is mined from salt domes beneath the floor of the Gulf of Mexico, where submarine oil and gas also abound. In 1965, 16 percent of the free world's petroleum came from wells on the sea floor; for 1975 the figure for submarine oil production will be more than doubled.

Deeper mineral deposits also are of potential interest. Among these are manganese nodules, some of them as big as grapefruits, covering vast stretches of the ocean floor. Some occur at depths of less than 1,520 meters (about 5,000 feet), but most of them lie 3,000 meters (about 10,000 feet) deep and beyond. The nodules also contain other metals, such as molybdenum, nickel, copper, cobalt, and iron, as yet outside our reach. Closer to realization may be the lifting of the phosphorite nodules that exist in billions of tons at shallower

depths, some close to the coast of California and others not far from other shores. They could be valuable as fertilizer, since phosphates are crucial to plant growth and our land-based supply is limited.

Though mostly occurring only as traces, many of the 92 basic elements of matter are contained in sea water itself in greater or smaller proportions. Theoretically it is not impossible to extract these elements; for instance, a cubic mile of water from any ocean contains $90,000 worth of gold—but a multiple of this would have to be spent to recover it. Because of their dilution, the same is true of most other metallic and non-metallic elements, with the exception of magnesium and bromide. The United States now takes all its supply of the former from sea water, and 75 percent of the world's supply of the latter also comes from the oceans.

Along the dry, warm coasts of many seas, ocean water has long been evaporated to obtain salt. The practice is becoming less prevalent, though, because less and less salt is used in food preservation, and also because salt mines and subterranean brine wells appear to be a more economical source of salt than the sea. More and more sea water will be evaporated in the future, all the same to slake a growing thirst for fresh water.

Desalinization of sea water is expensive. In some regions of the world, nevertheless, it is already economical, and many millions of gallons a day are being produced, notably in Texas, Aden, and other arid regions. Several different desalinization methods are being tried at present, each with its peculiar advantages and disadvantages. It seems clear that the increase in the number of people throughout the globe, coupled with their wish to have the advantages of Western technology, will so boost the world's demands for fresh water that the price paid for it will rise very sharply indeed. Inasmuch as the price of desalinization decreases with the size of the plant, fresh water from the sea will soon be economical in many places, at

least for those close to the seashore where it need not be pumped far either inland or upward.

In speculating about possible sources of energy to drive the enormous desalinization schemes of the future, it should not be forgotten that the dynamics of the sea itself may be lent to the production of power. The tidal ebb and flow, the ocean's response to the gravitational pull of moon and sun, could be harnessed to produce electricity. Long, narrow bays lend themselves best to the utilization of these extraterrestrial forces. A successful tidal power plant now operates near the mouth of the river Rance in France. Passamaquoddy and Cobscook bays, both opening on the Bay of Fundy along the border between Maine and New Brunswick, have already been considered possible locations for a large-scale tidal power project. There the conditions for a hydropower plant are provided by differences in water level between high and low tides of 12 meters (around 40 feet) and a narrow bay mouth where dams can be built—350 million kilowatt hours of electricity per year could be derived from this particular tidal power plant.

Another potential source of power lies in the temperature differences between surface and deeper tropical waters. The driving force for the turbines of such an installation would be the difference in the respective vapor pressures of the water in the cold water beneath and the warm-water layer above. There are few suitable shores for these installations, however, even if they were to become economical, and engineers point to heavy hydrogen as a more likely oceanic power source, one that would be the base of atomic fusion reactors.

As desalinization processes and shallow marine aquaculture develop, man may also take to the surface of the sea for living space. The growth of world population on the present scale should be expected to continue, say the experts, for at least one and perhaps two more generations. Between 20 and 25 billion people might well have to be accommodated a hundred years

from now. Not only will the population continue to grow, but people will be congregated in cities rather than spread evenly over the continents, and their demands for water and other commodities will be high. One way to relieve urban congestion and the attendant problems of supplying water and energy may be to settle man on the seas. Such cities of the future would float on the oceans, near the land to begin with, but later perhaps built farther out over the continental shelf. There would be vast outlying fields of algae and there might be industries to extract the deposits of the ocean floor. To the possible production of energy from ocean water should be added the use of solar energy transformed by algae into organic matter, to be fermented by bacteria into methane, a gas that can be burned or used as raw material for chemical industries.

At present the territorial limits of many countries include the continental shelf beyond their shores but not the waters above it. New legal concepts will have to be developed for the sharing of resources in and under the sea before we can colonize the oceans in the manner just proposed. At the same time, cities on the sea are not science fiction; they could be realized with today's technology, and building them would certainly be almost a routine task for the technology of tomorrow.

The reason for going to live on the sea will, of course, be the rapid increase in human numbers. The same technology that admits of building floating human anthills will also furnish man with improved birth-control techniques and allow him, theoretically at least, to achieve a stable human population, one that is in equilibrium with the carrying capacity of the biosphere. Although it is true that this carrying capacity appears elastic and amenable to expansion by technology—that is, even though more people are starving than ever before, more people also are better fed than ever before—there is a

final limit. Eventually we shall have to come to terms with the fact that the globe, improve it as we may, can maintain only a limited number of people at a time. But before we can apply to mankind limitations that seemed perfectly obvious when applied to the numbers of fish in a pond or of cattle on a range, we shall be pressed to try many new ways of improving our utilization of space and resources. One of those new ways, with profound influences on culture and civilization, will surely be the conquest of the ocean's top layers by man, and his intimate acquaintance with what lies below.

This book has been written to evaluate, in the light of present knowledge, some of the developments that are probable, others that are possible, and still others that are conceivable though not likely because of complications. In pursuit of this aim we shall first take a closer look at the oceans and some of the processes that take place there. We shall at the same time examine as well some of the methods and instruments that were used to gain this knowledge.

Because of their importance for the future of ocean sciences and technology, we shall go on to examine diving in its various aspects—including all manner of deep-ocean research submarines, as well as scuba, the means by which man can move freely in the sea—and we shall give special attention to the problems a man faces, whether free or enclosed in a shell, when he goes beneath the surface of the water.

A realistic look at sea life and its potentials for food and industry with glimpses into the past will follow, including the scope of aquaculture and the impossibility of extracting plankton for human food in an economical way in the foreseeable future. We shall then expand what we have touched upon already, namely, the ocean bottom as a storehouse for minerals, including oils, and gases. Since it is agreed that all fossil fuels will be used up one day, perhaps within ten or twenty generations, we must also examine in some detail the potentials of

power locked in the sea. Finally we must deal realistically with the uses of the sea as a supply of water for drinking and for flushing—a subject that will lead to weather modification and other prospects.

For the immediate future, though, there are other things to consider. We have altered the surface of the earth. In many places we have scarred the land, despoiled it and made it ugly. In a few places, on the other hand, we have improved on nature. It is generally supposed that technology can give us substitutes for dwindling raw materials—plastics in place of metals, and so on; and the sea is bound to provide us with sources for some of these. However, the problems may not be so much the quantity of materials available to us here and there in the environment but, as we extract them, of maintaining or improving the quality of our surroundings.

1

The Edge and Below

Waves

Gently lapping on a sandy beach, erasing the fragile footmarks of a passing sandpiper, breaking with dull thunder against the face of a steep cliff—waves are what we think of as the sea. They are, of course, only one aspect of the ceaseless movement of water in the ocean, and while not yet seriously considered as a source of power, as the tides have been, their interaction with the shore affects man in various ways. There is the beach itself, golden and calm in the summer sun; there is also erosion, flooding, and shipwreck. All too often there is destruction resulting from man's imperfect understanding of how to build on this meeting place of land and water. They are many things, beach and wave: the end of one world and the beginning of another; the very embodiment of change.

The largest waves, which have never been measured exactly, supposedly exceed a hundred feet from trough to crest. In the constant westerlies of the Antarctic Ocean, waves of up to 50 feet are not rare, whereas a transatlantic steamer passenger who experiences 30-foot waves will have had a very rough crossing. Though the sea is rarely without a breeze, the viscosity of water and the force of gravity require a minimal wind velocity before waves begin to form. In a breeze of less than a meter per second no waves appeared in controlled test tanks; when the wind exceeded this speed by a very small amount, distinct waves appeared.

Whoever considers in detail the characteristics and attributes of water waves must first distinguish between the direction and speed of the wave as such and the direction and speed of the water particles that compose it. He must further distinguish between swells or waves in the open ocean, where there is no bottom to create friction, and the same water movements near the shore, where friction comes into play. Swells are waves that were caused by winds far away; they persist for a long time even in the absence of a breath of air, and they are without sharp crests. In the eastern North Atlantic, the center of origin of the swell is the stormy region near the Azores, where waves are produced that may reach the coasts of England, Africa, or even Newfoundland in less than a day. In the open ocean the very biggest waves with breaking crests are often the results of a strong wind acting on an already existing swell. The physical properties of water admit only the formation of waves of a certain steepness, beyond which the top of the water breaks, dissipating much energy in the foaming.

Most wave speeds have been ascertained at sea by clocking the progression of particular crests with regard to a vessel's known length; a wave that travels at a speed of 30 feet a second is already very respectable, but peaks of wave progression at more than a hundred feet per second are known. Their length—that is, the distance from one peak to the next—can be equal to half a mile; and the period of these giants—that is, the time after which one crest replaces the next at a fixed spot—is just over twenty seconds.

From a ship it is easy to check, after a fashion, on the movement of the water itself, simply by following a small particle of wood or seaweed with the eye. It will move up and down the entire height of the wave, but will appear to remain almost stationary, as compared to the rate at which the wave itself travels. The water particles that carry the floating object in turn describe circular paths with a radius that depends both

on amplitude (one half the wave height) and on wave length (the distance from crest to crest). These circular paths decrease rapidly with depth, and waves of 30 feet or more can hardly be measured 300 feet below the surface. The motion of water particles in smaller waves is dissipated much more quickly; a wave with a velocity of 9 or 10 feet per second, a length of about 18 feet and a height of just under a foot will have disappeared at a depth of 10 feet. This fast dissipation of wave motion with depth clearly supports the case for submarine freight transport.

Though slower by far than the wave itself, the water particles still move a little in the same direction. They travel with the wave when they are in the half circle above its mean depth, but move counter to it below. Not only do the radii of movement decrease with depth but so does the speed with which the circular paths are described, so that each water particle does not return to its starting point but moves in a slow spiral in the direction of the wave.

These are the conditions where the water is deep. When the water particles strike bottom on their circular paths, the circles turn into increasingly flattened ellipses until the waves roll in upon the shore. There the waves advance and retreat only horizontally, though impeded by friction. Most shores are irregular in both outline and bottom topography, and the breakers may approach the coast at an angle, leading in places to rip currents and undertows. But whether the breakers roll in straight or on the bias, they dissipate tremendous force in the process; a 25-foot swell with a wave length of 500 feet and a speed of just under 50 feet per second will expend in breaking on the shore a force equivalent to over a million horsepower per linear mile. With such forces regularly, and stronger ones occasionally reinforcing them, it is surprising that the sea is not more destructive of human artifacts along its shores than it actually is.

The most destructive waves are commonly known as tidal waves, though they have nothing to do with the tides. They may be caused by unusual wind conditions, such as hurricanes or typhoons piling up water against low-lying coasts or narrow inlets; submarine volcanic eruptions—landslides. Earthquakes under the sea can also set up real waves of tremendous proportions. On August 26 and 27, 1883, after some smaller warning eruptions earlier in the year, the volcanic island of Krakatao, in the Sunda Straits between Java and Sumatra, exploded. The interaction of cold water and red-hot lava must have produced enormous submarine vapor bubbles which, on exploding, set off waves with long and short periods. Some of these must have reinforced one another to reach a hundred feet in height, destroying towns, villages, and settlements in the surrounding islands, with a death toll estimated at 36,000. The long waves reached Cape Horn and could be felt halfway around the earth, at recording stations in the English Channel thirty-two and a half hours after the event that had produced them. Krakatoa is still rumbling; it became active again in 1927, and it, or the very prevalent neighboring volcanic and seismic sites, may well cause great catastrophes in the future.

Tides

The tides have wave length, amplitude, and periods, which are always many times longer than the periods of wind-driven waves. The various tide-producing forces act at regular intervals of from twelve hours to six months, depending on the positions of sun and moon in relation to the earth.

The only celestial bodies close enough to exert a noticeable gravitational pull on the earth are the moon and the sun; together with the earth's own gravitational and centrifugal forces, they largely shape the tides. The sun, being much

farther away, exerts at most only about half the pull of the moon in spite of its much larger mass.

The apparent orbiting time of the moon is 24.84 hours; high tides occur both under the moon and halfway around the globe, opposite to where it appears in the sky. At the former location, the moon's attraction exceeds the earth's gravitational and centrifugal forces; in the opposite location, the moon acts with a minus force of attraction, as it were, and permits the centrifugal force of the earth itself to produce a region of high water. The semidiurnal periods of the moon-caused tides are 12.42, or close to twelve hours and thirty minutes.

The action of the sun is similar to that of the moon, except that its apparent period of revolution is so close to precisely twenty-four hours that the semidiurnal tides caused by it occur every twelve rather than every twelve and a half hours. Thus sun and moon reinforce each other at some times and counteract each other at others, so far as their tide-producing forces are concerned. This coincidence happens roughly every two weeks, when spring tides occur at the time of a full or new moon. Thereafter the moon-tides lag by some forty-five minutes every day until, fourteen days later, there are tides with the water rising at neap high tide only to a fraction of the spring high tide. Neap tides occur at the moon's first and third quarters—that is, when sun and moon stand 90 degrees apart with respect to the earth—and counteract each other's gravitational effects.

If these forces with near 12-hour periods were alone responsible for the tides, calculating their extent would be simple. But, in addition, the shape of the sea bed and of the land, as well as the 24-hour cycle of sun and moon, lunar fortnightly, monthly, and solar-annual influences also come into play. These last produce the extremely high spring and the extremely low neap tides of the equinoxes. There are also effects of the declination of the moon—that is, the change in the

moon's apparent zenith position, from latitude 28 North to 28 South.

On most shores there are roughly two high tides a day; but in many parts of the earth the tides have different periods, as a result of the interplay of the controlling forces with the shape of the shore and the ocean bed. Thus, for example, Copenhagen, and some spots on the coast of Vietnam have only one tide a day.

When the tide rises along a coast with an inlet, a channel, a narrow-mouthed bay, or the mouth of a river, the water naturally rushes in, and later ebbs out again. The highest known tides occur in just such places. Mont-Saint-Michel in France has a mean high tide of 12.6 meters; on the Severn River in Great Britain it is 13.1 meters; and on the Bay of Fundy in Canada it is 13.6 meters (all these figures over forty feet.) The Bay of Fundy at least—and probably the same is true of all areas of great difference in tidal levels—is subject not only to the tides themselves but also to tide-caused and tide-reinforcing standing waves or oscillations. These oscillations amplify the changes in water level; whether such amplification occurs or not depends on the shape of the basin. Clearly, at any rate, such places are well suited for tidal power development, and the possibilities have been investigated to some degree.

Another effect on tidal currents that remains to be mentioned is the so-called Coriolis force, which is due to the earth's rotation, and which deflects streams of wind or water that flow along the earth's surface, to the right in the Northern and to the left in the Southern Hemisphere. For instance, the high tide progresses through the English Channel from the west-southwest; as it enters the narrows, the front toward France leads and has higher highs than prevail on the coast of Britain. The deflection due to the earth's rotation can even produce circular patterns of high tides, such as may be seen in the North Sea, where the basin between Great Britain and Scandi-

navia contains three such circles of tidal progression. Similar patterns of tidal currents have been observed near San Francisco.

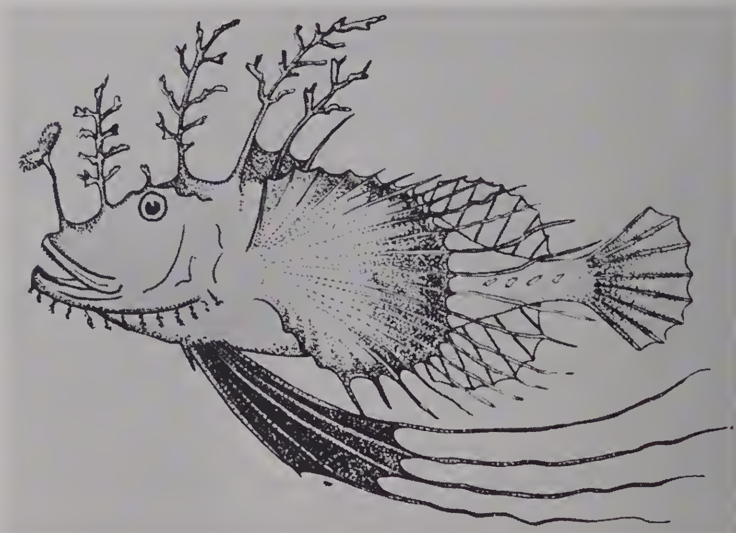
The tides are most important to man in seeking a landfall when ending his journeys on the seas—much routine surveying and charting of them has been done and is still proceeding. But they are also important as an influence on the behavior of marine animals. Many fish cease feeding when the tides change; some feed only at rising and others only at falling tides. In a few instances even the spawning act depends on the tides. The grunion, a little fish occurring along the California coast, spawns exactly at high tide on the second, third, and fourth nights following the high spring tides. The female deposits her egg pod in the sand just above the waterline and the male then fertilizes it. The eggs hatch in two weeks, but only if they are washed into the sea by the tides at the next dark moon. The delicate adjustment to an intricate set of conditions implicit in this behavior has been summed up by Arthur Pearse in his *Animal Ecology:** "If spawning occurred just before the highest tides, when the beach was being eroded, instead of just after, when the beach was being built up, the eggs would be washed out of the sand before they had developed for a fortnight. If spawning occurred at the very highest tides (dark of the moon), the eggs might not be exposed for a month, or even two months. If grunions laid their eggs during the day, they would be exposed to the attacks of gulls and other predacious animals."

Ocean Currents and Water Masses

Although the tides regulate the activities of some marine animals, the presence of their food, and often the presence of the animals themselves, is due to much vaster water move-

* McGraw-Hill, New York, 1926.

ments than the tides, namely, the ocean currents. For instance, after the last glacial period, Bermuda was recolonized fairly quickly by corals and by other tropical organisms because of its being reached by tongues of water that came from the Gulf Stream, carrying a variety of plant spores and animal larvae from southern climes. Another island, Madagascar, owes much of its rich shore fauna to currents that sweep across the Pacific. Many fish and other small organisms are, in fact, adapted to these travels; they have flotation devices, such as gill or fin filaments, that serve to increase their surface and prevent them from sinking (Fig. 2) or, like the young of the spiny lobster, which spends up to two years in the surface currents, they are flattened and transparent, and become transformed into bottom



Tierwelt der Nord und Ostsee

Fig. 2. Floating larva of a toadfish, just under an inch long. The fish will later settle on the bottom. Note the filaments on the fins which are believed to counteract sinking.

dwellers only when they grow older. Because the transformation into the adult form takes place on the high seas, most of them perish and sink into the abyss. Yet the ocean currents will bring a few to the right places with the right bottom at the right time to maintain a population where one existed before and also to colonize new ground.

The major surface currents that continually transport gigantic water masses across the seas are driven by steady winds, caused in their turn by what may be called the general air circulation of the atmosphere. It is made up of interlocking wind systems produced by the interaction of unequal heating in polar and equatorial regions with forces engendered by the earth's rotation.

At the equator the sun has its fullest effect on the earth: there the surface of the sea is heated; water evaporates, rises, and condenses into towering clouds that may burst in intense tropical downpours. The rise of the warm, moist air reduces the pressure so that winds—the trades—blow toward the equator from north and south. The doldrums, this region where the trade winds meet, are zones of calm or of light variable winds. The sailing vessels of old were often caught and becalmed there, and the word also came to denote a state of depression.

If the earth were stationary, the trade winds would blow straight from the north in the Northern and from the south in the Southern Hemisphere. But since it rotates from east to west, the angular momentum due to its rotation is greater on the equator than near the poles. Air currents that blow toward the equator are thus deflected toward the west, and north winds become northeasterlies in the Northern Hemisphere while the south winds south of the equator will blow from the southeast. (Winds are named after the direction from which they come.)

Winds that blow toward the poles, however, will be pulled along with the rotating earth more swiftly near the equator

than in the slower-moving higher latitudes: such are the so-called westerlies of the North Temperate Zone. In the Southern Hemisphere, by analogy, certain winds that blow from the north will become northwesterlies.

Interactions of the vast air masses are involved in the general air circulation—some slipping one over the other, some sinking, and some rising as they form an interrelated pattern of so-called convection cells. Above each hemisphere are three such cells that interlock, more or less, as one goes poleward from the equator. These are the trade-wind zone, the zone of prevailing westerly winds, and the region of the polar easterlies. They generate the winds that drive the ocean currents.

The absence of land from the path of the westerlies of the Southern Hemisphere—occurring below Africa and Australia and the southern tip of South America—makes this zone, the "roaring forties," one of the stormiest regions of the world. With minimal obstruction by land, the westward flow of southern ocean water results in an almost circumglobal cold ocean current. By contrast, the large landmasses of Asia and Africa in the Northern Hemisphere make the northern Indian Ocean anomalous in a different way, so far as its winds and currents are concerned.

In the rest of the world's seas, the North and South Atlantic and Pacific oceans, the trade winds and the westerlies shape the surface ocean currents into patterns one would expect from the wind directions. On either side of the equator there is a warm broad, westward-flowing equatorial current. Between the two, in the center of the doldrums, with no winds to drive the water, lies the so-called equatorial countercurrent, a narrow but occasionally deep-reaching stream that moves eastward and opposite to the two equatorial currents, at speeds of between two and nearly three miles an hour. Recently it has been estimated that it is the largest single current in the equatorial Pacific, transporting more than three quarter of a billion gallons of water a second. The equatorial countercurrent arises because

the westward-flowing equatorial currents pile up the water they carry, raising the level of the sea by so much that a countercurrent, draining off some surplus water, comes to flow and wedge itself between the two trade-wind-driven currents, even without encountering land.

When the equatorial currents then reach the east coasts of the Americas, of Asia, and (in the southern Indian Ocean) of Africa, most of their waters are deflected to the north or the south to form the prominent warm, swift currents that lead much of the trade-wind-driven waters back into the zone of the westerlies, where they return across the ocean, clockwise in the Northern and counterclockwise in the Southern Hemisphere. Among these are the Kuroshio Current in the North Pacific, which makes Japan warmer than it would otherwise be; the Agulhas, along the coast of Southwest Africa, and the East Australian Current, which sweeps around the Tasman Sea. In the South Atlantic there is the Brazil Current, which turns eastward off the coast of Argentina and mixes with the cold, eastward-flowing stream of the South Atlantic, eventually to feed the South Equatorial Current once again, and be deflected toward America by the joint action of the southern trades and the bulge on Africa's equatorial east coast (Fig. 3).

The best-known poleward deflection of trade-wind-driven waters, though, is the Gulf Stream. It is born in the confluence of two water masses, both brought across the Atlantic by the North Equatorial Current: one is the Florida Current, which rises from the pile-up and hydrostatic head of waters driven into the Caribbean and is forced out between the northern tip of Cuba and the Yucatán peninsula; the other is the Antilles Current, which flows past the northern shores of Puerto Rico, Hispaniola, and Cuba and outside the Bahaman banks, to join the Florida Current beyond the Straits of Florida.

In 1770 Benjamin Franklin, who was then postmaster general for the colonies, prepared the first reasonably accurate map of the Gulf Stream—though there had been more fanciful

Drawing based on Walford and Sverdrup, Johnson and Fleming

Fig. 3. Some of the important surface currents of the world's oceans. The stippled regions are those of high nutrient content and consequently have much plankton and fish.

maps before, showing legendary maelstroms and whirlpools. His aim was to speed the voyage of the mail packets from England by providing their captains with a means of avoiding this current that impeded their westward progress.

Two centuries and countless oceanographic observations later, the Gulf Stream is the most intensively studied surface current, yet much about it remains to be discovered. We do know that it leaves the continental slope off Cape Hatteras and flows northeast toward the Grand Banks. According to the noted Woods Hole oceanographer Columbus O'D. Iselin, only this mid-section ought to be called the Gulf Stream, and beyond the Grand Banks it should be called the North Atlantic

Current. Its water masses are sped to the northeast by the westerlies, but they soon break up into several components.

Even before reaching the Grand Banks the Gulf Stream loses a large part of its waters in an eddy toward the south and southwest, sweeping past Bermuda, which is thereby endowed with a milder climate than the islands should have by virtue of their latitude. This eddy encompasses the famous Sargasso Sea, in whose deeper waters are the breeding grounds of all the eels from Europe and America. It is not full of weeds, nor is it a center of wrecked but floating vessels of past ages, as popular belief once had it. The Sargasso Sea is interesting in fact because it is surprisingly barren—a matter to which we shall return when discussing ocean fertility.

The North Atlantic Current divides still further so that large tongues of its water flow toward the coast of Spain and Portugal; some even enter the Mediterranean through the Straits of Gibraltar, but most of this portion of the current turns southwest off the coast of North Africa and enters once more into the North Equatorial Current of the Eastern Atlantic, thence to be driven anew toward America by the force of the trade winds.

Another component of the North Atlantic Current turns northeast and divides again. One arm flows past Ireland and Norway up into the Barents Sea; the other, called the Irminger Current, turns northwest, past the south coast of Iceland, finally losing itself in eddies around southeastern Greenland and mixing with the cold Greenland Current that sweeps down from the north.

Before leaving the subject of the Gulf Stream and the North Atlantic Current, some comment should be made on the firmly rooted idea that these currents keep the European climate milder than it ought to be by virtue of latitude—a notion taught, at least, in my own school days.

Although the northeastward-flowing surface waters of the Atlantic have an influence on the climate of Europe, that influence is by no means so direct as was once thought. In fact,

it would appear that the relations are the reverse of those assumed previously. During the past thirty years the North Atlantic surface circulation has slowed down, the Gulf Stream transport has decreased, and the European climate has warmed slightly. It is too early to be quite certain of these relationships, but we do know that the warm water masses to the right of the Gulf Stream, and the relationship of the southward currents from the Arctic, as well as relative evaporation and condensation from large areas in the Atlantic, are all at least as important as the Gulf Stream in determining the climate of Europe.

To complete the broad pattern of surface circulation in the oceans, the cold currents should also be mentioned. Water is removed from the eastern coasts of the continents by the large warm-water currents that flow eastward and are driven by the winds prevailing in the latitudes of the westerlies. Consequently, at least in the Northern Hemisphere, the cold currents that come down from the north slip between the warm currents and the coast. This is what occurs off Japan and off North America, where many vagaries of the eastern coastal climate can be explained by this cold intruder between the land and the warm water offshore.

Some of the water, as we have seen, is returned by means of the westerlies into the large-scale circular current pattern of the ocean basins. Some water is diverted, however, and to keep an equilibrium new water is drawn in. In the Southern Hemisphere part of that new water originates in the Antarctic and is brought into currents that sweep along the western coasts of South America and Africa to end up in the two big equatorial currents. But deeper water also contributes much to what eventually become the equatorial current systems.

As the trades drive the water westward, away from the western coasts of the continents, the result is a pressure deficit, which leads to the upwelling of water masses from along the continental slope. Into them have sunk the remains of dead

surface organisms that have decomposed, so that these rising waters are rich in nutrients. As they come up into the sunlight, raised by the westward flow on the surface, there arise tremendous plankton "blooms" that are fed on by invertebrates, which in turn are fed on by small, medium-sized, and very large fish. The world's greatest single fishery, the Peruvian anchovy industry, owes its existence to the cold Humboldt Current, which sweeps out to sea from the South American coast under just such circumstances; and several other large fishing grounds likewise rely on upwelling or admixing of cold deeper water. Zones of high fertility can arise in still other regions, but they are typical of those where shore-skirting cold currents turn seaward to form cross-ocean streams, pulling up deep water along the shore in the process.

As long as the sun heats the air and the sea, strong permanent wind patterns will keep the surface currents flowing, and as a result will impart motion to deeper water layers. In some areas water is renewed by upwelling, as was mentioned; in others, the surface water sinks and feeds deep currents. The Gulf Stream, the Brazil Current, and the Kuroshio all cool down as they flow out of the trade-wind belt. Their cooling water sinks and feeds the deep-water masses of the ocean, a phenomenon that appears to be most pronounced in the Antarctic.

Vast amounts of ice form around the edge of the Antarctic Continent, but the ice does not contain any salt—rather, it is crystallized fresh water. The unfrozen sea adjacent to the ice has become saltier, though, and the cold, salty, and therefore denser or heavier water sinks along the slope of Antarctica. It forms the so-called Antarctic Bottom Water, which flows north toward the tropics, hugging the bottom because it is cold. In fact, the thermometer reports it to be slightly below surface freezing temperature. Oceanographers have recognized this dense cold water, with its typical high salinity, far up in the

South Atlantic basin. Yet another water mass that sinks in the Antarctic is formed where the Brazil Current meets the westerlies-driven surface stream.

Rapid surface cooling is characteristic of this convergence, though the temperature does not go so far down as it does at the edge of the permanent ice. This distinctive sinking water mass, known as the Antarctic Intermediate Water (or AAIW, for short), does not subside as deeply as the Antarctic Bottom Water, but it also flows northward. It can be recognized by its characteristic temperature and salinity even north of the equator, in the Caribbean region and beyond.

Convergences are typical of the meeting of two surface currents, and they lead to the downward transport of water just as the divergence of two currents or the flowing away of a current from the land leads to its upward transport or upwelling. Of still other forces that may cause the formation of deep currents, one is high evaporation such as takes place in the Mediterranean Sea. The only route by which water can pass into and out of the Mediterranean is through the Straits of Gibraltar. There the surface current flowing into the Mediterranean runs at an average of about two knots (two nautical miles per hour). It is a tongue of water from one of the arms of the North Atlantic Current. Intermittently high evaporation due to strong dry winds produces highly saline water, so dense that it sinks as the downward components of convection currents in the several basins of the Mediterranean Sea. The incoming water from the Atlantic amounts to 1.75 million tons per second, far more than are accounted for by the net losses by evaporation after precipitation and inflow. Therefore water must again leave the Mediterranean. The Suez Canal amounts to no more than a pinhole, and the Black and Caspian seas have no outlet at their far ends, so that the Straits of Gibraltar remain the only possibility. Sure enough, measuring instru-

ments lowered in this passage to a depth of 200 meters (about 600 feet) reveal a current flowing out over the sill at a rate nearly as great as that of the inflow, the difference being equivalent to the net losses by evaporation.

The deep water flowing out of the Mediterranean is cold and highly saline and is therefore so heavy that it flows downward along the continental slope of Africa. There it mixes with other, deeper, intermediate water masses at a slow enough rate to be identified, on the one hand, along its path straight across the Atlantic, where it joins tongues of the AAIW, while another component of the deep water from the Straits of Gibraltar can be traced even into the South Atlantic.

The Measurement of Temperature, Salinity, and Current

Probably the most typically routine operation aboard an oceanographic vessel is the lowering and raising of water sampling bottles and thermometers. These furnish most of the basic data for physical and to some extent even for biological oceanography—that is, temperature, salinity, and amounts of oxygen.

Water masses are recognized by their temperatures and salinities, or, as oceanographers say, their T-S characteristics. With salt content or salinity of sea water being expressed in parts per thousand of dissolved substances, average sea water has a salinity of 35 parts per thousand, also written as 35 0/00 in contrast to % or percent, meaning that for each thousand parts of water there are 35 parts of various dissolved minerals, mainly common salt (NaCl).

The admixture of salt and a lowering of temperature both change the density of water, so that a cold-water mass with many dissolved substances will be heavier than one with few. Thus a slight fall in temperature and an increase in salinity

reinforce each other to create considerably heavier and therefore sinking water masses.*

The water sampling bottle is really not a bottle but a tube that is open while being lowered so as to reduce resistance and allow the water to flow through it, and that can be hermetically closed at a desired depth. Since the intention is to obtain also the temperature of the sample at the moment of sampling, not as it is influenced by being pulled up through the much warmer surface water, it is necessary somehow to record the thermometer reading that prevailed at the moment the water sampler was closed. Of the many different samplers that have been tried that combine these properties or satisfy them singly, the most universally used is the Nansen reversing water bottle, named for its inventor, the explorer Fridtjof Nansen. Combining a water sampler with a thermometer, it is simple enough to be almost foolproof, yet has the accuracy of a precision-made instrument. Its thermometers, for instance—there are two, and we shall soon see why—register differences of 1/100 degree Centigrade.

On the side of the vessel there is usually a small platform for the oceanographer to stand on as he clamps the Nansen bottles or other samples onto an adjoining cable which may go down to a thousand meters or more (Figs. 4 and 5). There are standard depths for Nansen bottle sampling: at 10-meter intervals near the surface, at 100-meter intervals between 200 and 1,000 meters, and at more widely spaced intervals below that. The bottles are attached by the top and bottom to the cable along which they are lowered. The top attachment is loosened by the impact of a hollow brass weight that rides down on the

* The differences in salinity between these layers are—to the layman—surprisingly small. For instance, the AAIW at about 1,000 meters is between two and three degrees Centigrade and has a salinity of around 34.34. Below it, down to 4,000 and 5,000 meters, lie the Antarctic Deep and Bottom Waters, with temperatures from 2 to minus 0.5 degrees C., and salinities of 34.65 and 34.8 0/00.

Woods Hole Oceanographic Institution

Fig. 4. A Nansen bottle about to be lowered into the ocean from a research vessel. Here the oceanographer is adjusting a hammer or messenger-weight, which, when released, will fall on the cable and trip the next lower Nansen bottle.

Woods Hole Oceanographic Institution

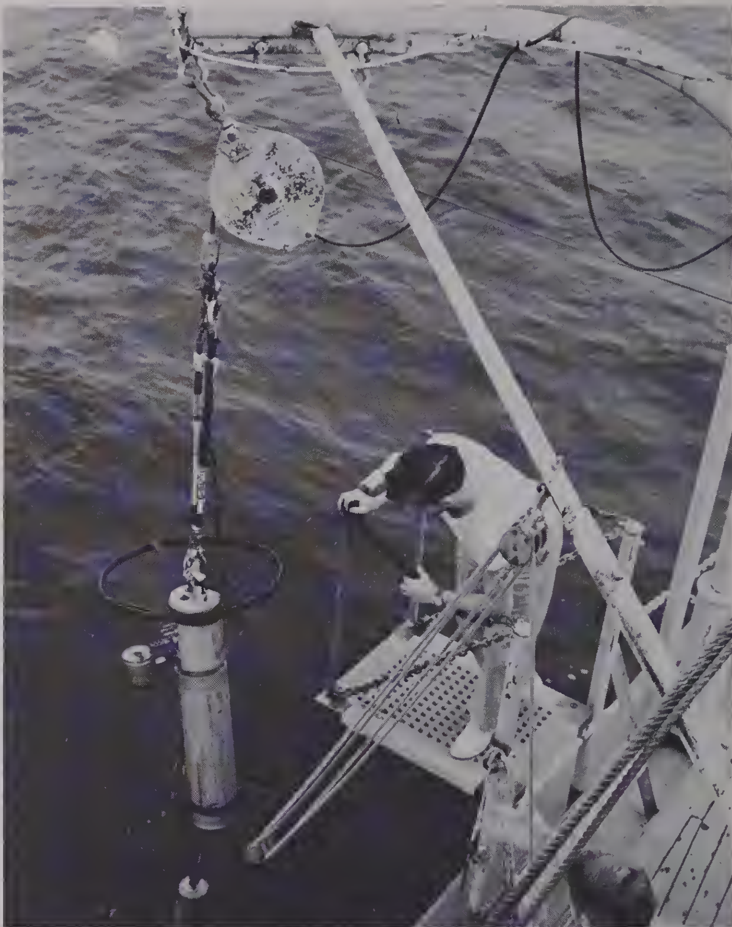
Fig. 5. Water sampler being lowered into the deep waters of the North Atlantic Ocean during a wintertime research cruise. This sampler is used to retrieve a large volume of sea water at varying depths for later study and analysis.

cable. When this "messenger" strikes the top fastening of the first bottle of a series, it causes the bottle to pivot around its lower fastening, thus setting in motion another messenger so as to activate the next bottle and, in the same manner, those below. The releasing of the sampler to pivot around its lower cable attachment not only releases the messenger for the bottle below but also closes the tube hermetically and thus secures the water sample.

The previously mentioned two thermometers are encased in a protective metal grillwork on the outside of the bottle. One of them, the so-called reversing thermometer, has a capillary device that maintains the mercury column at the temperature reading of the moment the thermometer is pivoted. The pivoting of the bottle upon the impact of the messenger thus secures both water and temperature samples at the desired depth. The second thermometer is an ordinary variety, which gives the temperature at the time of later readings, so as to furnish a small correction factor, thus taking into account the difference between the reading of the reversing instrument at the sampling depth and the reading at the surface.

The Nansen bottles are taken off the cable while they are being raised. As a precaution, the operator usually wears a wristband with a harness snap to be attached to the bottle before it is removed from the cable, to avoid losing any of the bottles—a single one of which costs several hundred dollars.

If the cruise is undertaken to answer questions on biological oceanography, chemical analyses of the water samples will be mainly to discover nutrients, such as nitrates and phosphates, and perhaps trace elements as well as dissolved oxygen. If the questions have to do with chemistry, the mineral content—mainly that of sodium and chlorine—will be determined either by routine titrations to be based eventually on comparisons with a universal standard, the so-called Normal Water, or by measuring the sea's electrical conductivity, which varies with the amount of salt it contains (Fig. 6).



Woods Hole Oceanographic Institution

Fig. 6. Salinometer being retrieved aboard the research vessel *Crawford* of the Woods Hole Oceanographic Institution's fleet of ships. The salinometer is used to take and record measurements of the salinity of sea water at various depths in the oceans.

In contrast to some lakes, the sea generally contains ample oxygen for all forms of life at all times, so that shortages are not a problem. An important variable to be assessed is the change of temperature with depth. Of particular interest is the surface layer, which is heated by the sun and often undergoes abrupt and pronounced temperature changes. These can be measured rapidly with the bathythermograph. The word is constructed from Greek roots and means, literally, "depth-warmth writer" —an accurate description of what the instrument does as it is lowered through the upper 150 meters of the oceans. The "writing" is traced on a small slide of smoked glass by a device sensitive to pressure—and thus to depth—coupled to a temperature element. There are now disposable bathythermograph units; they are lowered from the moving ship, and the depth and temperature changes they register are transmitted electrically to the topside recorder. At the end of its tether, at 150 or 200 meters, after it has done its duty, the unit is disconnected and sinks into the abyss. The low cost of transistor electronics, paired with speed and simplicity of operation, makes these disposable elements economical, though to some of us more old-fashioned scientists their use may still appear a bit wasteful.

Though temperature and salinity measurements can delimit water masses, and can even tell something about their movements, a direct assessment of the speed and direction of currents is still necessary. Some hints came accidentally. For example, fisherman's floats, clearly of Japanese origin, turned up on the west coast of North America, and the icebound remains of wrecked vessels were carried southward from the far north where they had met their doom. But these accidental drift markers revealed little detail of the current's course. About a century ago the systematic release of drift bottles was begun; since then they have been released in large numbers.

Drift bottles are weighted down with sand so that they will

not project above the surface, thereby offering resistance to the wind. Each one contains a card instructing the finder to fill in the location and time it was picked up, and giving the address to which this information is to be sent. A number indicates the place and time of release, so that the movement of the current can be charted by a comparison of release and pickup locations. Many drift bottles are lost, but whoever picks one up is likely to comply with the instructions, for the satisfaction of knowing that he is participating in what may be a large and important experiment.

Drift bottles, and likewise certain more refined drift devices equipped with sea anchors to reduce further the influence of winds, can be used only for surface currents. Deep currents, the objects of much speculation by such mid-nineteenth-century scientists as Alexander von Humboldt, have to be measured by other means. Their general pattern can be calculated with the help of deep-water samples, as already described, but their boundaries and their exact course are hard to determine without the actual tracking of submerged floats.

Advances in electronics and underwater sound-emitting and receiving techniques led, about ten years ago, to the perfection of such a device, known as the Pinger—a deep-water buoy that emits a sound signal that can be tracked from a surface vessel. After determining from water samples the density of the water mass to be followed, it is possible to weight the aluminum tube float so that it has the same density as the water in the deep current. The sound signal, usually one lasting two milliseconds and repeating itself every two to three seconds, can be picked up with special receivers, and with repeated cross bearings the course of the deep current in which the Pinger floats can be charted. Surprisingly fast deep ocean currents have been traced in this manner; for instance, at 2,800 meters (just over 9,000 feet) under the Gulf Stream the water flows south at a speed of a mile an hour; and near Bermuda, in still deeper

water, one 4,000-meter Pinger traveled 60 kilometers in forty hours, or nearly a mile an hour.

Still other current meters rely on the force of the moving water to turn a delicately balanced propeller, or a series of cups on the spokes of a wheel somewhat like those of an anemometer, the instrument that measures the speed of the wind. Since it is to be let down and cannot be read continuously, such a device must be coupled with automatic revolution-recording counters. It also must be equipped with a vane that sets and keeps it in the flow of the current. The more advanced and recent current meters are so fashioned that an underwater camera takes time-lapse pictures of the revolution counter as well as of a compass that indicates the position of the device and hence the direction of the current. Not only changes in direction but also in the speed of the current can thus be ascertained at considerable depth.

Another rapid-current meter, which so far has been perfected only for surface current measurements, relies on minute electrical currents generated while a stream of salt water flows through the lines of force that represent the earth's magnetic field. The amount of electricity generated is proportional to the speed of the water current, a fact that enabled William von Arx, a Woods Hole oceanographer, to develop a delicate ink-writing current meter, called the Geomagnetic Electrokinetograph (GEK), which is attached to a vessel and gives a continuous record of the strength and direction of the current through which the ship is passing.

Depth Measurements

Long before currents were measured or even speculated about, men sought to know the depth of coastal zones, estuaries, and harbors. They used hand sounding, a method probably as old as the building of boats, but one limited to about

twenty fathoms even with well-cast lead weights and a nylon line. Sounding in deeper places was tried when explorers ventured onto the high seas; Magellan, for instance, tied together six sounding lines of the sort used in his time and tried with a 2,500-foot line to plumb a spot in the ocean which we now know to be around 15,000 feet deep. Later attempts by great navigators such as Cook and Bougainville likewise met with little success, and the ocean was thought to be immeasurably deep. In certain parts of South America Ross paid out 8,600 fathoms of line (more than 50,000 feet) with 76-pound weight attached without touching bottom; in other places the bottom was reached at 2,425 fathoms. The South Atlantic Ocean is not so deep as might be indicated by Ross's unsuccessful soundings; the force of the current, and probably the drift of the vessel, caused the line to run out at an angle so that it never reached bottom.

Machines have been invented for deeper soundings from a stationary ship, preferably in a calm sea. Since fine line will diminish drag if there is a current, silk was originally favored. Thus wire, such as piano wire, was first used in 1874 by the Navy survey ship *Tuscarora.* (The wire, incidentally, is wound on a drum of specified circumference so that the length released can be recorded by revolution counters.)

Sounding with such machines became much more accurate when it employed an invention made around 1850 by Lieutenant Brooke of the Navy. One of the difficulties had been the exact gauging of the moment when the cannonball used as weight hit the bottom, indicated by the slackening of the line. With thin lines to reduce drag and to speed the descent, and with heavy weights, many a cannonball, and with it the sounding, was lost. Brooke's simple device called for the sacrifice of the cannonball to recover the line. The cannonball was pierced and a protruding rod was inserted into the cavity. The ball was suspended in such a manner that it became unhooked as the

rod descended into the bottom and as the cannonball itself touched the substrate. This event slackened the line so perceptibly, even at great depth, that it became possible to pull up the rod, which slipped through the center of the cannonball with ease. Since the rod penetrated the bottom before coming unhooked, Brooke was able to attach to one end a scoop with a valve that closed when the rod was pulled up, thus retrieving a small sample when the bottom was soft.

In 1856 soundings made in this way were used to determine the best path for the first transatlantic telegraph cable, laid between Newfoundland and Ireland. From the small samples of bottom material taken at that time it was found that most of the so-called telegraph plateau was covered with the minute shells of dead planktonic animals, making the bed a suitable location for laying the cable, with no currents to disturb it.

Brooke's idea of releasing a weight as it struck bottom, along with devices for releasing and rewinding the wire, were refined during the second half of the nineteenth century and the early years of the twentieth. Thus by about 1930 fairly accurate soundings taken in many places had produced large-scale and reasonably accurate information on the shapes of ocean basins, on the location and depth of deep ocean trenches, high ridges and sea mounts, and on the continental slopes and shelves. Twentieth-century wire-sounding machines could make the weight descend at 100 fathoms a minute. Even so, really deep soundings, including the recovery of the wire, took many hours and often had to be abandoned because of difficulties in maintaining the ship's position.

Exploring with Sound

Compared with earlier depth finding with weights, the invention in 1911 of echo sounding, attributed to the American physicist Reginald Fessenden, is like the step from the airplane

of the Wright brothers to a modern jetliner. The weight could descend at 100 fathoms (600 feet) a minute; a sound pulse travels at a speed of about 700 fathoms (4,200 feet) a second. The principle is simple. A device placed on the hull of the ship emits sound pulses, and another such device receives them. The vibration, which rebounds from the bottom and strikes the ship again shortly after its emission, is registered by an underwater microphone, called a hydrophone. The depth of the water below the ship is determined by the formula $d = vt/2$, with d as the depth, v the velocity of sound in the water, and t the time between the emission of the sound pulse and its reception.

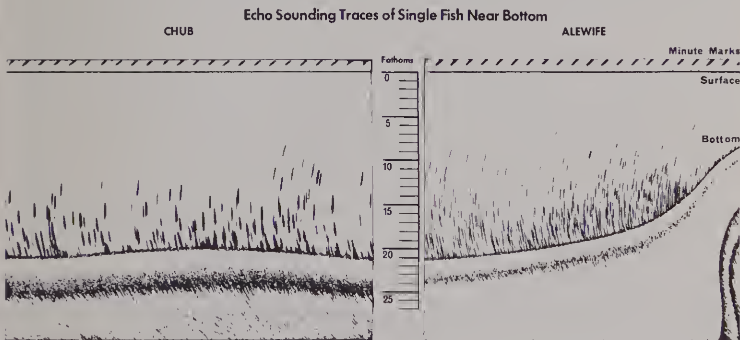
The difficulty with audible sound—up to 10,000 pulses or cycles per second—is that the pulses travel from the ship's hull like a succession of imaginary spheres. If the underwater surface is horizontal or only slightly sloping, it is possible to determine the depth quickly and accurately; but if there is a steep slope to starboard or to port, the echo will reach the hydrophone on the ship before that from the bottom surface immediately below it. The way to overcome this dilemma is to use ultrasound of from 20,000 to 40,000 cycles per second, which can be directed in a narrow beam.

When the sound or ultrasound echo is received, the hydrophone transforms it into an electrical charge, which activates a stylus on a calibrated moving chart so as to draw a running profile of the bottom, with the depth readable from the calibrations along the height or width of the chart. Obviously, since echo sounders allow for a running profile of the sea bottom, and since radio direction finders and gyrocompasses allow for very accurate triangulation of a ship's position, the making of exact maps of the sea floor is now relatively easy and can proceed at some speed.

The device has other uses and advantages. The reflection of a sound beam depends on its encountering an object with a dif-

ferent density than the element through which it travels. The bodies of fish, with hard bones, on the one hand, and gas-filled swim bladders, on the other, also cause echo reflection (Fig. 7). Schools of fish, then, can be detected with echo sounders, and even the position of a trawl in mid-water can be monitored in relation to a school of fish. Wrecks on the bottom can be spotted also, at least in fairly shallow waters where the resolution of the device is great enough.

Underwater sound can be used not only to map the bottom and to locate such things as fish and wrecks but also to explore the sediments of the sea floor. For this purpose, instead of using a sound source from the hull of a ship, powerful explosions are set off at or below the surface. Their vibrations are reflected from the several underwater layers, and even from the earth's crust beneath the sea. The disadvantages of using



Records courtesy of Exploratory Fishing Section, U.S. Bureau of Commercial Fisheries, Ann Arbor, Michigan

Fig. 7. Traces of a modern White Line Echo Sounder. It suppresses the features immediately below the bottom under which it makes a white line, thus revealing the fish that hover above the bottom.

Chubs are a few inches longer than alewives. More importantly, their swim bladders are of different sizes. Therefore, the two kinds of fish produce different echo traces and a skipper can make a good guess about what kind of fish happens to be near his vessel.

explosions—the problem of safety and the difficulty of setting them off in rapid, pulselike succession—do not apply to the use of very powerful pulse generators in the sound-frequency range; these can penetrate as much as three quarters of a mile beneath the bottom of the sea and obtain a profile of the layers of sediment.

Sampling the Bottom

The little scoop on Brooke's sounding device, already mentioned, was inadequate since it brought back only a very small sample and was of no use on rock or gravel. But in 1850 it was responsible for the surprising discovery that a large portion of the Atlantic was covered with the silicious shells of diatoms. Since then more exact and detailed observations of these sediments have given rise to new theories concerning the formation of the ocean basins, and their probable age. For instance, the echo-reflection method revealed that the diatom layer in the northeastern Atlantic basin, represented mainly by the species *Globigerina* and now generally called Globigerina ooze, is 5,000 feet or more thick. Sedimentation rates are now estimated at a minute fraction of an inch per year—suggesting that these portions of the ocean bottom have remained submerged for several million years at least.

Samples of the ocean bottom are obtained by devices of two kinds. First, there are surface samplers that pick up bottom materials effectively to a depth of half a foot at most, but that may cover areas of up to four or five square feet. Equally shallow sampling dredges that are pulled over the ocean floor take only what is in the uppermost layer. These are mainly used to ascertain the kinds and numbers of animals living on and in the upper layer of the deposits. Also, incidentally, they reveal what the bottom is made of. Samples of the second kind

consist of thin tubes that are driven into the bottom by their own weight, by the force of a vacuum, or by light explosives. These encompass only a very small area, but they reach depths of over a hundred feet and retrieve samples of sediments with their fossils from past geological ages.

Luckily much of the ocean bottom is amenable to grabbing, dredging, and coring, since rock or large boulders are relatively rare and occur mostly near the coast, on portions of the continental slope, along submarine ridges, and in some canyons. Yet deep-water dredging is difficult because the wire must be paid out at an angle and may need a length of nearly twice the depth to be measured. Dredging at 30,000 feet, as the scientific crew of the *Galathea* expedition did in 1952, and having to pull in something like 50,000 feet of wire with the dredge at the end is quite a chore, though the satisfaction of seeing creatures perhaps never seen before amply makes up for the effort.

Grab samplers, which enclose and scoop up the sample, are often made of shovel blades or of the two halves of a horizontally placed trough, which close either by spring action or by a special closing device that comes into operation as a result of weight release as the grab is pulled up. Grabs are heavy, and to penetrate into the bottom, where their weight is already reduced by the buoyancy of the water, they are built so that the water can stream through them while they descend. The larger ones, which sample an area up to half a square meter (a bit under five square feet) may weigh up to a thousand pounds (Fig. 8).

One of the hazards of using grabs is that a stone may lodge between the closing blades, leaving a small crack and causing all the finer material as well as the bottom animals to be washed out on the way up. Incidentally, the main reason why grabs give only limited information on the nature of the bottom is that the animals scooped up in this way have to be separated

Woods Hole Oceanographic Institution

Fig. 8. Pulling a bottom sampler aboard a research vessel of the Woods Hole Oceanographic Institution.

from their substrate by washing and rinsing the bottom material through a series of graded sieves, from which the animals can then be gathered either by hand or with forceps—a process during which much of the mud and silt is lost.

The core samplers that bring up columns of bottom material are long, thin metal tubes, no more than a few inches thick at most, which have now been perfected to bring back long continuous columns of sediments (Figs. 9 and 10). At first oceanographers tried to sink them into the bottom merely by weight, but because of the buoyancy of water, and to some

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Fig. 9. Fifty-foot coring tube about to be lowered over the side of the research vessel *Atlantis II*. The tube descends vertically and upon contact with the ocean bottom heavy weights (foreground) are released to drive the tube into the bottom sediment.

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Fig. 10. Coring tube in vertical position about to be lowered from the research vessel *Atlantis II*. Tube is lowered vertically by cable.

extent because of the limitations of the winches available on oceanographic vessels, the tubes were able to penetrate only a few feet, the equivalent of no more than 100,000 years of deposition. C. Piggett of the Carnegie Institution of Washington has invented a core sampler that is driven to the bottom with small explosive charges and obtains cores to depths of ten feet or so. Unfortunately the friction between the core wall and the bottom material not only limits the depth but also distorts the layers and their exact relation to one another is of course important in unraveling questions of geological chronology.

About 1940 Borje Kullenberg and Hans Petterson of the Oceanographic Institute at Göteborg invented the Piston Core Sampler, which still drives the tube into the sediment by weight, but which is lined with plastic, thus redueing friction and making the later handling of the core easier. Furthermore, the water that is replaced by the bottom mud or silt as the corer sinks into the bottom is evacuated from the tube by being drawn into a vacuum or reduced-pressure reservoir, placed above the coring tube for this purpose. Cores of 100 feet or more have been raised with this device from various parts of the ocean floor by the Swedish research ship *Albatross* and by research vessels of the Lamont Observatory of Columbia University, of the Woods Hole and Scripps laboratories, and by Soviet scientists. They reach several million years into the past.

The Nature and Origin of Sediments

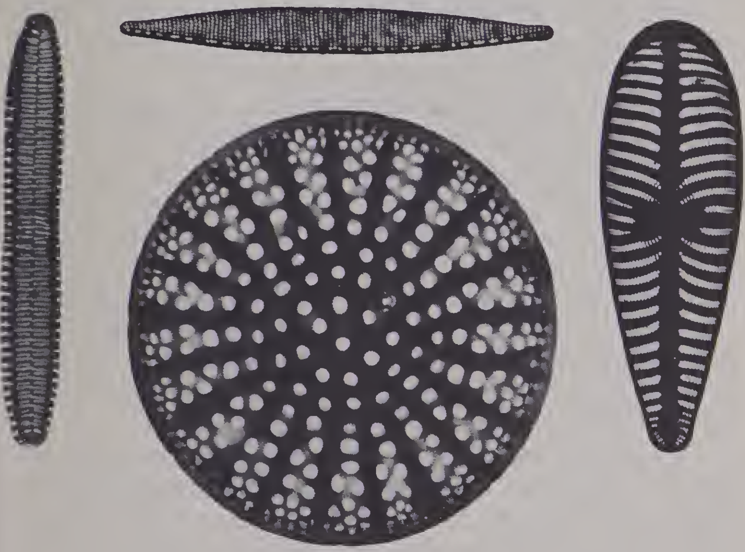
Submarine sediments are of interest because they allow inferences to be drawn concerning some events in the past of our planet, such as climatic changes, as these are mirrored in the succession of remains of cold- and warm-water organisms. Sediments are interesting also for their possible use by man; some of them contain submarine oil and some may, one day, be exploited for metals and other minerals.

Ocean currents notwithstanding, whatever falls upon the sea from the air, along with many of the durable remains of surface-dwelling animals—such as sharks' teeth and the calcareous and silicious shells of the microscopic animals that live in the sunlit upper waters—finally reaches the bottom. The inorganic components of bottom deposits are volcanic dust and ash, tiny wind-borne sand particles which may be blown to sea from adjoining deserts and, of course, the clay, silt, and sand eroded by rivers from their watersheds and carried out to sea. The most important of the sediments, both in volume and as a source of information on former conditions in the sea, are the shells and carapaces of plankton, the minute floating plants and animals that are at the base of the food chains in the oceans.

The prophet Isaiah, who said that "all flesh is grass," was no ecologist, but his insight applies both on land and in the sea—where the sinews, the teeth, and the scaly armor of mighty predators such as the tiger shark and the swordfish can be traced back to the plants that capture a portion of the sun's energy and transform it, along with the mineral nutrients that they also take up, into the protoplasm of their living cells. The familiar land plants on which we and all land animals depend are remote and ancient relatives of the unicellular plants of the sea—algae, diatoms, and dinoflagellates that float in the buoyant medium because they need no supporting structures. They can devote a greater proportion of their bulk to the all-important business of photosynthesis than is possible for a land plant.

The most important group of one-celled marine plants in the temperate and cooler seas are the diatoms, whose enclosing shells of glasslike silicon compounds often occur in minute stacks, like tiny boxes piled one on top of the other. In other diatoms the cells adhere loosely to one another along a narrow rim and have the look of miniature stars. The cases of dead diatoms as they sink bottomward are cleared of all organic remains (Fig. 11).

The plankton animals feed on the smallest algae, on one another, on bacteria, and to quite a considerable extent on the tiny fragments of organic material that are always present in the upper layers of the sea. For reasons that are not yet understood, silicious shells are the attribute of cold-water plankton; about 12 million square miles of the cold seas in both the Northern and the Southern Hemisphere are carpeted with silicious ooze. Closer to the equator 50 million square miles of the ocean floor are covered with calcareous ooze, largely made



Dr. E. F. Stoermer, University of Michigan

Fig. 11. Electron micrographs of silicious shells of diatoms. *Left:* a species of *Fragillaria,* 35 microns long. *Top: Nitzschia* sp. 40 microns long. *Center: Thalassiosira,* about 12 microns across. *Right: Gomphonema,* about 30 microns long. The individual organisms have varied shapes, from a flat pillbox (center) to those resembling spindles or clubs.

up of the tiny cases of the one-celled animal *Globigerina,* a relative of the amoeba.

In the great depths below 15,000 feet deep-sea chemistry and pressure seem to operate against the persistence of the calcareous shells, and approximately 40 million square miles of ocean floor are covered with a sediment that has been called red clay. It is rich in iron and manganese compounds and also contains volcanic ash and pumice, which must have floated for a long time in surface currents before finally sinking. Some silicious remains of microscopic plants and animals also occur in red clay, and so do some larger calcareous remains such as sharks' teeth and whales' earbones, though the minute lime-lacking shells of the dead plankton do not persist.

Submarine sediments accumulate slowly, but apparently at differing rates. Echo and explosion sounding of subsurface layers of the sea bottom, coupled with calculations of the rate of erosion on land and of the quantities of eroded material that could have settled under the sea, tell us that the red clay in some places under the Atlantic is about 12,000 feet deep and has been accumulating at a rate of 0.3 inches per thousand years—for at least 500 million years. These calculations assume that the erosion in earlier epochs was the same as it is today; but since it may have been either faster or slower, they may not be accurate.

It is strange—and came as a surprise to oceanographers—that deep sediments in the Pacific, which is believed to be the oldest of the three large marine basins, appear thinner than in the Atlantic. This may be the result of errors in echo-derived information about the extent of these layers, the result of some mishap with oceanographic equipment. Every now and then a long piston corer comes up bent, carrying at its tip just enough trace of the hard surface that caused the bending to show that the soft sediments frequently contain bands of lava, the result

of submarine eruptions. These bands are so hard that they reflect sound waves in the same way as does the underlying earth's crust, even though they may be relatively thin and may be underlain by one or more layers of soft sediments. If so, those hidden sediments are unfathomable with the instruments now at our disposal.

The bottom can now be photographed by means of self-tripping, precision flash cameras that are let down to great depths (Fig. 12). When such a camera is at a certain distance from the bottom—usually between three and ten feet—the shutter is opened by means of a foot with a spring that extends from the frame. Since there is, of course, no telling what may be within range at any instant, some deep-sea photographs have produced unexpected information: that sand ripples occur at a depth of many thousands of feet, indicating the presence of a current close to the bottom; that fish can live at surprising depths; and that bottom invertebrates are much more common at a depth of around 18,000 feet than had been imagined.

What may be a still more important finding from these photographs is the existence of certain peculiar rounded concretions—most of them the size of golf balls, but some, especially in the very deepest mid-Pacific, much larger—that stud many areas of the deeper ocean floor. Samples of these nodules revealed them to be concentric deposits of ferric hydroxide and manganese peroxide with admixtures of yet other metals including some that are rare on land. Some of them had a shark's tooth, a piece of pumice, or the shell of a single former plankton organism as a core.

It would appear that manganese nodules are forming continuously; according to current estimates, their quantity is truly staggering. Most of them lie on the floor of the Pacific, where they may amount to well over a hundred billion metric

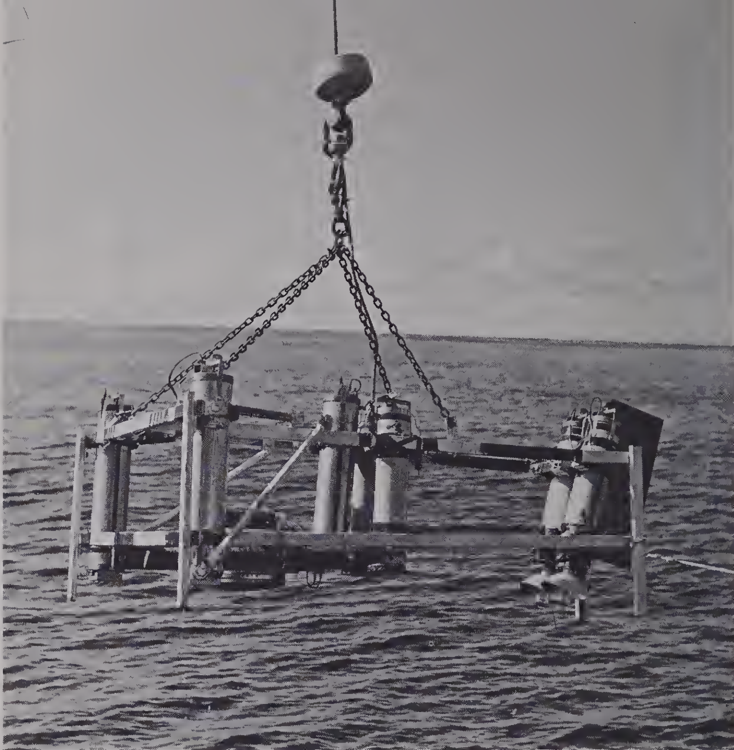


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Fig. 12. On board the research vessel *Atlantis II*, a large underwater camera being lowered to bottom. Note "pinger," disk-shaped instrument in center of rig, and lights at bottom. Pinger is used to determine height of camera from bottom. Other cylinders contain stereo cameras and batteries.

tons. Smaller deposits, perhaps another hundred million tons, occur in the Indian and Atlantic oceans. Further photographic exploration of the ocean floors may show that these estimates are too high, though technological optimists argue that they are too low. The nodules represent a tremendous potential metal resource, and with the gradual dwindling of ore deposits

on land the question is naturally asked whether or not they can be exploited. The realization of this feat is augured by the rapid progress of undersea technology and the present-day mastery of the ocean's upper layer—the subject of our next chapter.

2

Probing the Dark

Diving Gear

It is a rare swimmer, especially in tropical waters, who does not become entranced upon first slipping on a face mask and swim fins to take a look at the underwater scenery and its strange inhabitants. Those who later become scuba enthusiasts joining the new fraternity of those who watch life beneath the surface of the sea had a famous forerunner in antiquity, Aristotle's pupil Alexander the Great, who is said to have descended into the sea in a diving bell that allowed him to observe the life of the sea floor. His mentor may very well have accompanied him on what would then have been the first in a long series of ventures by amateur and professional fish-watchers. The Macedonian king is also reported to have used divers to destroy harbor defenses during the siege of Tyre, one of the earliest episodes in the long history of undersea warfare.

The development of diving equipment, begun in antiquity, led in 1830 to the invention of the diving helmet attached to a closed suit and connected by a hose to an air pump at the surface. This gear, its use limited to depths of about 250 feet, has not changed substantially since then and is still used in most salvage work. Self-contained diving gear for individual divers—as opposed to underwater vehicles—was designed soon afterward. One version using compressed oxygen and a device

to eliminate carbon dioxide from the exhaled air, was perfected around 1880. It resembles the respirator used by miners and firemen, and is useful for shallow dives because it is compact. As a diving tool, however, it is limited because pure oxygen inhaled under pressure at close to two atmospheres and beyond —that is, at depths greater than thirty feet of water—induces convulsions and unconsciousness.

Other versions of the self-contained diving apparatus use compressed air. Of these devices, which have truly opened the door to undersea exploration, the latest and best engineered is the aqualung. In Jules Verne's *Twenty Thousand Leagues under the Sea,* the crew of Captain Nemo's submarine use what they call the Roquayrol apparatus. This was not a flight of Verne's fancy but had already been invented and put to use by two Frenchmen, who called it the Aerophore, before the novel was written.

A later milestone in the invasion of subsurface waters was passed around 1920 when Guy Gilpatrick, an American, began spearfishing for sport. He wrote occasionally for the *Saturday Evening Post* and lived at Cap d'Antibes, where he kept open house for an international coterie. He and his friends, who wore close-fitting goggles and used hand-driven spears for their underwater hunts, were the earliest of the skin-diving clubs that became numerous first in France and then all over the world.

It is no coincidence that the Cousteau-Gagnan aqualung, the latest version of the apparatus which permits a man to become, for a limited time, the next thing to a fish, chiefly owes its development to a man who grew up by the clear waters along the Côte d'Azur. Diving in the Mediterranean is as old as the cities and towns along its shores. Sponges, which have to be dived for, were much used in Greece and Rome; red coral has been a prized adornment since early times, and so has mother-

of-pearl from the shells of many different kinds of mollusks. The famed Tyrian purple used to dye the woolen robes of emperors and nobles was extracted from a small cyst near the head of a marine snail, which likewise had to be brought up by divers.

Jacques-Yves Cousteau was already an experienced enthusiast for free diving when in 1943 he tried out the first aqualung, which he and the engineer Emile Gagnan had perfected. Rubber foot fins had been introduced a few years earlier, as had face plates that covered both nose and eyes and gave better vision than goggles. Cousteau, who is at once both a visionary and a thoroughly practical man, recounted his first lung dive in *The Silent World*, where he wrote of flying without wings, of standing upside down on one finger without feeling his weight, and of having invaded a new world that awaited exploration. The feelings he expressed are shared by all lung divers on their first dive, and perhaps never entirely leave them.

The principle of the aqualung and other compressed-air scuba gear is to deliver air to the diver at the same pressure as that exerted on him by the water, at whatever depth he may find himself. As pressure in the water increases by one atmosphere with every 30 feet, a diver at about 180 feet would experience seven atmospheres, or more than 80 pounds of pressure per square inch over and above that of the atmosphere at sea level. Because human tissues are somewhat more dense than water, and are resilient as well, so long as the air delivered to the lungs is at the proper hydrostatic pressure the surface of the body is scarcely affected by the weight of the water column overhead. The air in the aluminum cylinders carried on the back of a scuba diver is compressed to 200 atmospheres, and is released into the inhaling tube clasped between the teeth and lips through a pressure-sensitive

demand-valve system. The diver exhales through the mouthpiece into another tube leading back to the regulator in the tank above his neck, where inhaled and exhaled air are separated by a rubber diaphragm. The air he exhales rises to the surface in bursts of silvery bubbles. The system is simple and relatively foolproof; its limitations are those inherent in respiratory physiology.

To the novice the most noticeable obstacle, though one of relatively minor medical importance, is an occasional difficulty in clearing the ears as one descends, and of eliminating the sometimes painful feeling of pressure. The Eustachian tube connects the middle ear with the pharynx and through it with outside air. If the tube is plugged, as it often is when one has a slight cold, the pressure of the water outside exceeds that in the middle ear as a diver goes down. Swallowing, a common practice of descending divers, will usually force sufficient air into the tube to equalize the pressure of the water with that of the air delivered by the lung regulator. When an experienced diver cannot clear his ears he refrains from diving.

Factors of still greater importance, since they limit the depth of the descent, the length of time spent at the bottom, and the speed of the ascent, have to do with the physiological effects of the solubility of gases upon human respiration. Normal air is about one fifth oxygen and four fifths nitrogen, with a trace of carbon dioxide and even smaller traces of rare, inert gases. Most of the oxygen in the blood is carried by red blood cells; but nitrogen is simply dissolved in the body fluids according to its own pressure. At atmospheric pressure a certain amount of the gas is found in all human tissues, and the amount increases as the pressure increases. At a certain level of nitrogen in the blood the gas begins to have an intoxicating effect, somewhat like that produced by alcohol; and beyond 130 to 160 feet, varying with the individual and with experience, the diver

begins to undergo nitrogen narcosis or "rapture of the deep." Beyond that depth, 30 additional feet down is equivalent to another cocktail, so that even an experienced diver may begin to lose his senses and to do senseless things, such as taking off his mask and offering the air to the fish. A diver with nitrogen narcosis may also lose his sense of up and down, perhaps because of the effect of pressure on the sense of equilibrium, seated in the inner ear. Some divers have indeed plunged to their deaths, for reasons that remain unknown but that most probably involved nitrogen narcosis and associated effects. Normally, though, a depth indicator on the diver's wrist allows him to anticipate and avoid the danger zone.

A second important effect of increased amounts of nitrogen or other gas in the blood and tissues is that they make it necessary to limit the speed with which a diver may come to the surface. If he rises too quickly, the gas that leaves the tissues because of the reduction in pressure forms bubbles that may be lodged in the joints, the blood vessels, and even the brain, rather than be eliminated through the lungs. It may take such various forms as pains in the joints, respiratory troubles, and nervous disturbances. Severe cases may even cause death. The disease is variously known as the bends, compressed air illness, or caisson disease—the last named from mishaps connected with the use of caissons or pressure chambers with open bottoms, such as were used during the nineteenth century in building bridge foundations and harbor installations. In order to keep water from entering the chambers, the pressure inside had to exceed that of the surrounding water. Out of ignorance, men were pulled up too fast to avoid the formation of nitrogen bubbles that produced the disease.

A free diver's air supply is limited, and progressively deeper dives curtail the working time at the bottom, since a diver must return to the surface in easy stages with predetermined pauses between. The Navy Standard Decompression Tables state that

one 50-foot dive for seventy-eight minutes is permissible without decompression, but that after working three hours at that depth the diver would have to stop for at least nine minutes at ten feet to eliminate the risk of the bends. Diving to a hundred feet without decompression is possible only if the time from leaving the surface to the beginning of the ascent is less than twenty-five minutes; staying for an hour or more at 100 feet requires three decompression stops between 30 feet and the surface. Together with the time at the bottom, this exceeds the time span afforded by the air supply of the largest scuba tank. Thus fresh tanks must be sent down, and must be exchanged for the empty tanks while the latter are submerged—an important maneuver that is mastered early in the training of scuba divers. The stops for decompression during the ascent, a routine event on many dives, are rarely pleasant interludes. After the work at the bottom a diver is tired and often cold as well, and there is nothing to see but the other divers circling slowly and looking at their waterproof wristwatches.

Caution must also be exercised against an excess of carbon dioxide in the lungs, and consequently in the blood stream, causing tissue poisoning and faintness, in addition to reducing the oxygen-carrying capacity of the red blood cells. Thus an adequate volume of air has to be available for the elimination of carbon dioxide as the lungs are ventilated. The deeper the dive the more air is needed for this purpose: 10 cubic feet of air at atmospheric pressure are required at 200 feet, as against 1½ at the surface. For this reason, and because of the increase in decompression time while surfacing from greater depths, the effective working or observation time on single dives becomes shorter and shorter as the depth increases.

Even while surfacing from shallow depth, or from one decompression stage to the next, a diver must never rise faster than the air bubbles he emits. Air expands as it rises, and if he were to emerge faster than the bubbles, the rapidly increasing

pressure in his lungs would rupture the delicate tissues. The consequences may be dire indeed; they range from slight damage, with some coughing of blood, to the complete disintegration of the thin lung tissue and its blood vessels. Thus submarine crews are trained in escape tanks to practice free ascent while observing these elementary rules, opposed though they are to the primordial urge toward self-preservation.

Gases other than nitrogen, especially those that are rare and chemically inert, such as helium and neon, do not cause intoxication when they dissolve in the brain. Consequently, divers for the Royal Navy were given helium mixed with oxygen for a plunge to depths of 600 feet in a flexible suit and helmet. Even though the "rapture of the deep" is avoided, decompression is still necessary, since air bubbles may form and cause difficulty when the pressure is released too rapidly. A young Swiss mathematics teacher, Hanns Keller, who breathed pure oxygen for a while before a dive, then combined various gas mixtures and switched from one to the other during the descent, reached a depth of 1,000 feet in a diving chamber off the coast of California. He even emerged from the chamber for a short while, using his breathing tube. The dive, spectacularly successful though it was, nevertheless ended in disaster after Keller's swim fin caught in the hatch of the chamber when he re-entered, destroying the airtight seal. His companion, Peter Small, died soon after reaching the surface, apparently as a result of a gas embolism and a lack of oxygen.

Recent advances in scuba technology include gear that uses liquid instead of gaseous compressed air. A diver with such gear can stay down five to six hours instead of the hitherto customary one or two, though he is still subject to decompression rules. Practically, the obstacles to swimming about safely in this unknown zone are on their way to being overcome in still other ways. The key to this feat is so-called saturation

diving, using gas mixtures other than air. There will be more to say about this in a later section on living under the sea.

Seeing Is Believing

Even though a single dive lasts but an hour or two, and is limited by the air supply in the tanks, already biologists, geologists, archaeologists, and others have logged tens of thousands of hours observing and photographing the underwater world. In consequence, firsthand information on shallow-water biology and geology has increased phenomenally since scuba became available after World War II. Also, miles of film have been exposed underwater, yielding, among others, the haunting documentary movies of Cousteau and Hans Hass.

Underwater scientists will become increasingly numerous now that many universities and research institutions offer training for divers. Foam rubber suits that rely on body heat to supply insulation, and others that are electrically heated, make diving comfortable; propeller-driven underwater sleds allow divers to cover greater distances than they could cover with fins; and special cameras permit them to record their observations.

The underwater camera can be directed by the observer to furnish records of specific events, rather than the haphazard pictures that lowered submarine cameras produced. A French engineer, Abraham Rebikoff, who became an enthusiastic underwater explorer after a distinguished topside career, has built a torpedo-shaped, propeller-driven, battery-powered camera that not only is equipped with fully automated filters and lights but also pulls the diver along as he scans the submarine landscape. When he wishes to take a picture, he stops or slows the drive and directs the camera toward its object, somewhat as though it were a gun. Self-contained lights

are necessary for underwater photography, since even a shallow layer of water filters out all but the blue-green band of the spectrum. When the scene is well lit, the photographs reveal that the blue-gray world 50 feet or more down along the slope of a coral reef, for instance, is in fact kaleidoscopically colored. In the beam of the camera light, yellows, reds, and purples appear which would otherwise be invisible since these same wavelengths are not present in the normal submarine light. Instead, they appear as a multiplicity of shades and fall into patterns whose significance for the inhabitants is yet to be explained.

Fishermen have devised their varied fish-catching devices mainly by a process of intuition, without knowing until recently just how they worked. Many observations of fishing gear in action have been made by divers who rode above the net on underwater sleds, or on the net itself (Fig. 13). They were able to tell the designers that a net rode too high or too low, that its meshes permitted the escape of smaller fish, as was intended, or that the meshes tended to become narrow and lozenge-shaped, thus retaining fish which were too small. Captain Cousteau, upon first watching a trawl go by, was appalled to see what a clumsy thing it was and how it tore up the bottom. Convinced that man will truly conquer the underwater world of the shallow seas, he and other diving pioneers look forward to better and more intelligently designed fishing tools.

On rocky ground, where nets may become entangled, fish traps are often used. The design of such traps may be improved as a result of watching how fish enter in quest of the bait and then sometimes find their way out again. They show panic upon first discovering that they are confined, and dart to and fro wildly, chafing their snouts on the trap's wire mesh. They come to the exit by chance and dart out, some to re-enter for another meal if any bait is left. Presently they may be seen going in and out freely; some may even make their home in the

William L. High, U.S. Bureau of Commercial Fisheries

Fig. 13. Bureau of Commercial Fisheries scientist clings to a moving experimental trawl. By working directly on the trawl, divers are able accurately to evaluate configuration and web strain. Also, biologists can easily observe fish within the net. Net speed is over 2 knots.

trap or may enter a second trap set in place of the first. Since most kinds of fish are observed to enter against the tide, traps may be fitted with a vane that will turn the funnel in the proper direction while it is being lowered to the bottom. Controlled experiments have also been made using traps with two funnels, one for each direction of the tide.

Scuba has also been used in counting the kinds and numbers of fish that live in an area. Such a census can become a check on pollution or other abuses of the aquatic habitat and may help to determine whether or not too many fish are being removed, either for sport or for food. For a successful fish count there must be a number of divers who know fish well enough to recognize a species on sight—a condition not always easily met. Before undertaking a census the area must be divided into lanes with tape or colored wire. The names of fish most likely to be encountered are listed in advance with a grease pencil on opaque plastic slates, leaving space for the diver to note miscellaneous encounters or surprises. Other devices for underwater exploration will be discussed in the following section.

Some fish, of course, may be hidden by cracks and overhangs, thus eluding a census taker; and others may easily be counted twice. The number of those hidden can only be estimated, for example, by poisoning some small but representative areas of the terrain covered in the larger survey; counting twice can be avoided through practice and through coordination of the divers' activities. Divers are instructed to keep abreast of one another, so far as possible, and not to count fish seen swimming toward them from an adjoining lane where, presumably, they have already been registered. A count must be repeated several times, and even then it will not be entirely accurate. The clearer the water, however, the more reliable it will be, and in any event it will yield more varied information than any other method yet devised.

Before the advent of scuba, the habits of fish and invertebrates had been studied by keeping them in aquaria. Now animals are observed in their natural habitats, and their behavior is filmed or otherwise recorded for later, more detailed analysis. For instance, the strange habit of parasite picking, especially by some species in the Wrasse family, has been

documented in this manner. These wrasses are brightly and conspicuously colored small fishes, suggestive of particularly dazzling artificial lures. As they swim with undulating motions toward such larger fish as groupers or moray eels, one would expect them to be gobbled up as a result of behaving and looking so much like bait; but evidently their appearance is recognized as that of a friend about to perform a useful function, for they are allowed to come close (Fig. 14). They then begin to gorge themselves on parasites picked from the bodies of the large fish. The association for mutual benefit goes so far that when a wrasse nudges at a grouper's gill covers, the

Dr. R. Schroeder

Fig. 14. Cleaning symbiosis. Parrotfish (*Scarus* sp.) in a reef recess with a parasite picker, in this case not a wrasse but a shrimp, probably *Periclemenes pedersoni.*

grouper obliges by extending them to give the picker access to the delicate breathing organs underneath. (The gills of the fish are naturally preferred by fish parasites because they are gorged with blood and because their walls, through which oxygen diffuses inward, are thin and can easily be pierced.) Barracudas may even permit the spaces between their razor-sharp teeth to be cleaned in this fashion without harm to the dental assistant, which departs unscathed once its duty has been performed.

Painstaking observation of parasite-picking associations have revealed one more strange fact—namely, that in some other small fish, unrelated to the wrasses, color patterns and swimming habits have evolved that make the two indistinguishable from each other. These pseudo wrasses, though, do not pick parasites; instead, they take bites from the soft tissue of the fins of larger fish and from the padded rims around their eyes. They imitate the dance of the parasite cleaners so expertly that they are allowed to approach within nipping distance, baring their fanglike teeth only at very close range, probably too close to be seen by the larger fish. These mimics usually live in small holes in the rock or coral, into which they retreat after a meal off their duped hosts.

Although the night world of the sea bottom was completely unexplored before the advent of free-diving equipment, it was already known, of course, that some marine animals are mainly active during the day, whereas others are active mainly at night. During the day snappers and grunts lazily move about in large, slowly milling schools whose members appear to have no interest in food. At night they leave their daytime haunts to spread out from the protection of the rocks onto the sand or mud flats beyond, where they forage for all kinds of invertebrates which, in their turn, are active by night rather than by day. The bright red squirrelfish, with their huge eyes, also emerge at dusk, and though they go less far afield than many

other species, they keep in touch with one another by means of gruntlike rasping sounds which also serve as a warning when a large enemy approaches. Plant-eating species such as parrotfish, on the other hand, sleep at night, when they can be touched and even lifted up without waking them. That they really sleep is shown by their breathing rate and their consumption of oxygen which at night is half or less of what it was during the day. At night some parrotfish secrete a protective envelope of mucus around themselves, a device that makes them less vulnerable to such night prowlers as the morays, which select their food chiefly by smell.

Sea urchins, looking like giant pincushions, with their purple spines, are fairly conspicuous marine invertebrates. They don't move about during the day, but at night they may be seen gliding in and out of a field illuminated by the cone of a searchlight, in their quest for food. Some sea urchins have bright spots at the base of the spine; these spots reflect the light as the animals move with surprising agility on their sucker-padded tube feet. The starfish and brittle stars, cousins of the sea urchin, are also much more active at night than during the day. A starfish, as it crawls about, may flip over, but soon rights itself by taking hold with first one and then two or more of its five feet. The brittle stars have longer and more slender arms than their stubby relatives, and their sinuous movements recall the snakes adorning the mythical Medusa's head. Coral animals also are nocturnal, coming out of the crystalline limestone fortresses they have built for themselves and weaving their tiny arms as they comb the water for the plankton that is their food.

Experienced divers who have worked at night report that sharks are more on their minds then than during daytime dives—as is quite natural since most sharks hunt mainly at dusk and during the night. They locate food both by smell and by following sound vibrations in the water. Sharks are most

dangerous after they have had a whiff of the odor of blood; then one will avidly pick an impaled fish from the spear of an underwater fisherman, even turning on a man when its feeding frenzy has been aroused through the senses of taste and smell. As a precaution, night divers do not spear fish, and they make it a rule to leave the water as unobtrusively as possible when a shark appears. Anyone who has had the opportunity to observe sharks both at dusk and during the day can hardly avoid the impression that they are more alert at dusk. Most sharks seen during daytime dives appear to cruise lazily, with sinuous swimming motions. As the light diminishes, they appear more alert; the movements as they swim become shorter and quicker, and they seem to follow a more direct path. It is not often that an experienced diver has trouble with sharks, for he respects these large predators so perfectly fashioned for their role in the marine environment, giving a wide berth to any shark that may seem in an aggressive mood. It may be that sharks are light-shy; at any rate, no serious mishap with sharks has been reported during night dives using strong lights.

As much as we have descended into the sea by day, and sometimes also at night, we have thus far no more than scratched the surface of what is to be learned with free-diving equipment, cameras, and other recording tools of the underwater world of the shallow seas. Such studies will be multiplied many times over in the years to come.

The Drowned Past

Every youth who puts on an aqualung cherishes the dream of finding and raising a sunken treasure; and some men, who though older in years may still be boys at heart, have done precisely that. The most spectacular one-man operation of this kind in recent years was mounted by Teddy Tucker of Ber-

muda, who found some ancient cannon between reef pinnacles. Digging farther with his bare hands, he brought up a sixteenth-century bronze mortar and a small bucket containing silver coins. On the same dive, as if that were not enough, he uncovered a bar of gold. He returned again and again to the spot in an old boat crudely rigged with a suction hose for removing the sediment. When this attempt at mechanization failed, he used a table-tennis paddle to fan the sand away. Tucker's perseverance and a diving skill perfected in salvage work were rewarded by the discovery of more gold and of an extremely valuable emerald-studded bishop's cross. This and his other finds are now on exhibit at the Bermuda aquarium.

Raising the cargo of ancient ships antedates the use of scuba gear; some notable finds were made long before. Even the nets of fishermen have brought up a gold cup and several bronze statues, either whole or in part. Helmeted sponge divers among the Greek islands have made finds of inestimable value. These men treated their treasures with respect and brought them up with surprisingly little damage. Most of their finds are now in the Greek National Museum at Athens.

Such chance finds, however, cannot be defined as archaeology. And the underwater quest for remnants of the past is now largely a scientific endeavor by men for whom the raising of archaeological treasures is only part and not necessarily the most important part of underwater exploration. That exploration is carried out by teams of geologists, who ascertain the nature of the sediments; salvage engineers, who recommend the right methods; and trained archaeologists, who supervise the mapping and the day-to-day work in such a manner that the traces of the past are reconstructed rather than disrupted. There must also be sizable teams of divers—who often are interested amateurs rather than professionals—because of the physiological limitation on dives to deeper sites, which permit only a short working period for any one man. Usually a doctor

is on hand to deal with emergencies brought on by the effects of decompression and other unforeseen mishaps.

The initial reconnaissance can be done from underwater sleds, self-propelled or drawn behind a surface vessel, with vanes that allow it to float above the site. The diver lies on the sled and makes sketches that can serve for laying the grid for later surveys, from which the observed position of objects will be triangulated in the grid (Fig. 15). The state of preservation of various structures must be determined in order to decide

University of Pennsylvania Museum—National Geographic Society Expedition

Fig. 15. Aqualung diver sketching on plastic the positions of labeled objects while hovering above an underwater archaeological site on which a grid has been laid.

what is the best way of raising an object so that it can later be reconstructed. Only by such painstakingly systematic means can information be obtained from underwater archaeological sites on the technology, art, commerce, daily living of ancient peoples who have left their traces on the ocean floor.

Many mistakes were made on early submarine digs—even by trained archaeologists, who did not realize, for instance, the vagaries of shifting and settling sands. They dug holes with slopes that were too steep, failing to anticipate that the mud stirred up by divers in such holes would linger rather than be carried away by ocean currents. Visibility thus became poor, and the intended systematic search degenerated into a scramble in which a diver took whatever he could while he was still able to remain below. Air-lift suction pumps, which work on the principle that an upward stream of air in a hose will draw water into it, somewhat in the manner of an aquarium filter, became a boon to the diggers, helping them to remove the sediments. There were dismaying experiences, though, before it was realized that old, waterlogged wood is very delicate and may be shattered by the suction force of such a pump.

Since most Mediterranean wrecks are of cargo vessels, and since much ancient cargo was carried in earthenware amphorae, the distribution of these variously shaped, flask-like containers tells much about ancient trade. Some amphorae had been sealed so well that they still held their original contents—wine, oil, honey, or fish sauces, to be mentioned later. They differ in shape according to contents and place of origin, and many carry potters' marks as well as the seals of certain trading firms. A few such firms appear to have dominated the shipping trade of Greece and Rome for decades, possibly even for centuries. Not only can trading practices be gleaned from systematic underwater exploration better than from the second- and thirdhand written sources now available, but the same is true of the ancient arts of shipbuilding and seamanship. Ships' riggings and hulls, of which no paintings have been preserved,

are depicted in mosaics and on vases, unfortunately with too much artistic license for anyone to deduce the minutiae of rigging and construction. Such features of antiquity can best be pieced together by a combination of archaeological engineering skills and many hundreds of aggregate diving hours.

Underwater explorations are likely to carry the investigation beyond ancient harbor installations and shipwrecks into prehistory at a time, during the ice age, when the sea level was several hundred feet lower than it is today. In those days vast amounts of sea water were locked in the icecaps and large areas of the continental shelf were above water. Caves that are now submerged in all probability were then the abode of our remote ancestors or the refuge of prehistoric animals. The limestone channels beneath the clear springs of Florida have already yielded some remarkable finds. Well-preserved mastodon bones and teeth lay in 200 feet of water under Wakulla Springs, and human remains and artifacts, some dating back almost ten thousand years, have been discovered there and at other, similar sites. Just how these remnants of the past came to lodge underneath limestone springs remains an unanswered question. Certainly it is not to be concluded securely from finding the bones of mastodons or tapirs, and some spear points nearby, that prehistoric man in America hunted these animals. That can be deduced only if bones are found showing spearmarks.

Other diving explorations of anthropological sites have been begun in the Great Lakes, which are really inland seas of fresh water. In the cold waters off Naomikong Point, in Whitefish Bay on the south shore of Lake Superior, an Indian settlement was discovered that must have flourished at the time of Christ. Shallow portions of the lake once were dry, just as were portions of the continental shelf, though for somewhat different reasons. The ice that formed from the ocean waters weighed down the land in the north and made it sink; the land began to rise again as the glaciers melted. Because of differences in

underlying geological strata, the rise was not uniform but proceeded faster along the northern shore of the lake than along its southern edge. Thus the lake basin became tilted, and the south shores were submerged.

The village site at Naomikong Point yielded pottery remains made of fired clay, tempered with small stone fragments and decorated, before firing, with various stamped or scratched ornaments. The shards permitted Drs. J. E. Fitting and G. J. Quimby, the two anthropologists who took part in the exploration, to ascribe the village to the Middle Woodland period of early American Indian culture and to date it somewhere between 200 B.C. and A.D. 200. Botanists who study the past climate and vegetation from pollen and sediments say that the lake bottom at that time was covered with a pine and hemlock forest, in which these Indians lived and hunted.

No reports on scuba explorations of caves drowned under the sea have yet been published, but some promising initial surveys have been made of such sites. Below sea level on the Rock of Gibraltar, for instance, it is suspected that there may be caves, possibly accessible to divers, that could have been inhabited as much as 60,000 years ago. If so, they may be of great importance, since caves above sea level in Spain and southern France have yielded some of the richest troves of prehistoric art yet found. With further improvement in free-diving techniques and cooperation among divers, archaeologists and anthropologists, it may be expected that exploration of submarine caves will bring forth as rich a harvest of man's past as digging in many ancient sites on land.

The Liquid Door

To dive for the sunken past, to prospect the sea floor for minerals, or to carry on biological research beyond the first 50 meters (150 feet) are possible only if semipermanent dry undersea bases are available, making necessary a different

approach to diving from the use of compressed air and scuba gear. Inside a station on the sea floor the pressure is kept equal to that of the water outside, which thus forms both a seal and a transparent liquid door through which the divers enter and leave the sea that surrounds them (Fig. 16).

The first 100 meters (328 feet) have now been conquered by the crew of Cousteau's *Conshelf III.* These men lived for twenty-two days in a helium-oxygen mixture at more than ten times atmospheric pressure. Many engineering problems had to

Fig. 16. The liquid door from *Sealab II* into the sea. A curious sea bass, attracted by the light, checks the entry hatch.

Official Photograph U.S. Navy

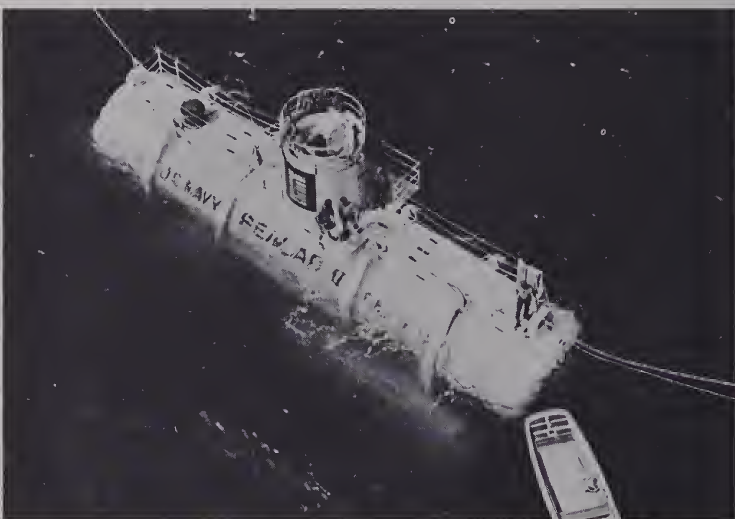
be solved, and much physiological research had to be conducted, before this and other sojourns on the sea floor could be successful. Some of the necessary data were gathered in sea tests; some were based on earlier helmet diving; still others had been compiled by a team led by Dr. George Bond, a Navy captain, who envisaged undersea colonies before Cousteau. The experiments of his team led to what Bond has given the name of "saturation diving," since the diver's entire body becomes saturated with the gases he breathes under pressure.

It must be remembered that the scuba gear, with which free divers ordinarily descend, makes use of compressed air. Diving below a certain depth brings about nitrogen narcosis, and after prolonged dives even at the safe depth of only 100 feet or so, the diver must pause during the ascent to permit decompression. Before 1910 the British physiologist J. S. Haldane, who was already prescribing decompression stages for helmet divers employed by the British Navy, had shown that divers who operated from a submerged base and at the hydrostatic pressure prevailing there could go out and return without any need for decompression. Nevertheless, normal compressed air has absolute limitations, quite aside from the problem of the bends, since at around 150 feet nitrogen narcosis sets in. At 100 meters (328 feet) compressed air becomes poisonous to a diver; and even if it didn't, the largest tank a man could carry would last him only a few minutes.

The discovery of helium and other inert gases at the end of the nineteenth century meant that at least in theory there was no longer any barrier to deep-sea diving. Until natural gas became a usable source of helium, the price of several thousand dollars per cubic foot was prohibitive. In 1919 the American inventor Elihu Thomson suggested that helium be used to replace nitrogen in diving mixtures, and a few years later the Navy began using animals in experiments with high-pressure mixtures of helium and oxygen. The extending of these experi-

ments to man, first in simulated environments and then in actual dives, in the past few years has made possible several successful temporary residences on the sea floor.

One such residence, the Navy's 1965 *Sealab II* (Fig. 17), at 63 meters (205 feet) off La Jolla Pier in front of Scripps Institute of Oceanography, has been well documented. Three teams of ten men each, including volunteer biologists from the Scripps Institute spent periods of two weeks each on the sea floor. Their leader, the former astronaut Scott Carpenter, remained for thirty days. The men breathed a mixture of 80 percent helium, 15 percent nitrogen, and 5 percent oxygen. On short dives a member of the team would take with him a hose that supplied the atmosphere of the living quarters; but for a longer sortie he would wear the Navy's Mark IV semiclosed-circuit breathing apparatus, combining backpack tanks with



U.S. Navy

Fig. 17. U.S. Navy *Sealab II* before submersion.

the proper helium and oxygen mixture and a carbon dioxide eliminator with inhalation and exhalation bags on the chest. The principle of the Mark IV is to reuse as much as possible of the valuable helium (about two thirds) by ridding the exhaled breath of its CO_2. Dives lasting as much as an hour are feasible with it at 63 meters (205 feet), the depth of *Sealab II.*

At 100 meters (328 feet) Cousteau's men on *Conshelf III* relied entirely on the breathing mixture of the underwater abode, carried to them through breathing tubes that trailed behind them. For a few minutes' emergency supply, however, each man also wore an aqualung. They say there had to be considerable adjustment and practice, for those used to free diving—as Cousteau's men all were—before they could manage their snake-like lifelines with ease.

Soon deep-sea divers may be able to wear less cumbersome gear when they leave their chambers, thanks to a closed-circuit breathing device, consisting of plastic bags and a much smaller tank than those used for compressed air, which is being developed. The apparatus will deliver a controlled mixture of oxygen and helium and will eliminate carbon dioxide, so that the expulsion of exhaled air will hardly be required. For short dives that begin in the deep but at atmospheric pressure, for example, in submarine escape situations with immediate sea-air rescue in prospect, there will soon be gadgets, thanks to Westinghouse engineers, no bigger than an oversized pocketbook. For saturation dives below 400 feet, however, even helium mixtures may have their limitations. British diving experts found that a helium narcosis sets in below this depth. Neon, another inert gas, which is still very expensive in large quantities, could be used when the diving range is to be extended still further.

Yet another way to allow men to become truly like fishes would involve the use of special fluids to fill the lungs and a simple surgical intervention; a small hole would be cut into the

diver's windpipe and his lungs would be filled with a solution that can hold large amounts of highly compressed oxygen. The Navy's diving pioneer, Captain Bond, in 1966 told a group of medical men that this process would allow divers to descend to 12,000 feet, to work there for one or two hours, and to do away with decompression. Animal experiments have borne out the technical feasibility of this method, and though there are, at present, no plans to extend them to human subjects, the surgery required is minor and does not impair air breathing when topside. It is indeed likely that volunteers will be found, in the future, to try out the method and that it will have the success George Bond predicts. With it, man would truly become a free agent to operate in the waters of the continental shelves and beyond.

Although helium mixtures make possible saturation dives down to a hundred meters or more, there are several disadvantages connected with breathing the inert gas. One of these is that a man's voice is distorted to a high-pitched squeak, because the helium atmosphere is thinner than air and allows sound to travel faster. The chambers of nose and throat resonate at other than their normal frequencies and the result is a sound like that of a fast-talking Donald Duck. The sound can be made more intelligible by cutting off its high and low frequency components and by shifting the entire speech spectrum toward a lower range during transmission. The deeper the dive, though, the more the helium voice is accentuated—as a result of pressure—and voice unscramblers will clearly have to become more sophisticated than they are today.

The deeper the dive the more the diver must also contend with the two main adverse conditions of cold and darkness. The water around *Sealab II* was between 44 and 56 degrees Fahrenheit and visibility ranged from 25 feet at best all the way to zero. Electrically heated suits are a necessity for future saturation divers. Some have been tried out that have batteries

in lieu of the customary weight belt worn by a diver, but they were only a qualified success.

Poor visibility is perhaps the most serious obstacle for work away from the base by divers breathing from scuba-like gear. Lifelines become entangled in the undersea growth and may even snag on coral. The light must be very strong; but even when it is, the particulate matter soon scatters the beam. As a result, there is a need for portable homing devices using sonar or some comparable electronic principle.

Porpoises, which are easy to train, have a built-in echo-sounding device so effective that they can distinguish between a dead mackerel pulled on a hook and a live one from more than two hundred feet away. One was trained to carry messages between topside and *Sealab II*, and also in mock trials to locate and bring home lost divers. The trials were promising, although too few were made to be more than that. Further experiments have borne out that a trained porpoise could be able to find a lost diver and guide him back to the base or slip him a lifeline emanating from home. Thus, one day the Navy may have its underwater watch-dolphins, analogous to the Army's Alsatian tracking dogs.

The occupying of the sea floor began in earnest in 1962 when two French divers lived and worked for a week in *Conshelf I* near Marseilles. Their home was a cabin placed at 35 feet below the surface and supplied with compressed air from above; no special breathing mixtures were used. In the same year Arthur Link lowered the Belgian diver Robert Stenuit in a submersible decompression chamber to a depth of 200 feet for twenty-four hours. The device had a helium-oxygen atmosphere and was equipped with a hatch that could be opened to let Stenuit emerge several times, using a tube to breathe through.

The next step in the underwater adventure was Cousteau's *Conshelf II*, set once again at 35 feet, but this time with five

inhabitants who stayed for thirty days. They worked in the sea for several hours each day, trapping fish, photographing and observing, diving to a hundred feet on compressed air and returning to their abode without decompression. Two other men went to live in a smaller, deeper station at 90 feet, where they used a special breathing mixture in which some of the nitrogen was replaced by helium. From there they dived much deeper without having to decompress upon returning to their base. Before coming up to the shallower station, however, they needed to breathe a special mixture for several hours. The men of the shallower station followed a similar routine before coming to the surface.

Conshelf II off Port Sudan in the Red Sea, must have been a weird sight indeed. Its main area was surrounded by four wings, somewhat resembling the arms of a starfish, with fish pens and plastic fish cages nearby, together with an underwater hangar for the diving saucer. The main house and the hangar were on stilts and emitted a continuous stream of silvery air bubbles. Living on *Conshelf II* was no hardship; it contained a sun lamp which every man used for ten minutes a day, a hi-fi set and, of course, communications via television and telephone with the tender moored overhead. In fact, the occupants under the sea felt more comfortable than the crew who took care of them above—Port Sudan being one of the hottest places on earth.

When the first photographic and film sequences of *Conshelf II* appeared, probably every scuba diver who had ever explored tropical seas wished that he could have stood at the windows of the starfish-shaped house and watched the multihued fish that came to visit (Fig. 18), or that he could have gone from there on night and twilight dives, waking up sleeping parrotfish in their coral shelter and observing the transformation of the reef from the daytime world to that of night.

After a few days, it seems, a man can become so completely

Official Photograph U.S. Navy

Fig. 18. Inside *Sealab II*. Fish are attracted to the lighted windows here as they were in *Conshelf II*.

at home in the shallow sea that he almost forgets he is wearing an aqualung. He can make friends with the fish, some of which learn to recognize without fail such an individual as a food-dispensing cook, even though he wears a rubber suit and a mask. The divers came to resent any removal of their finny companions, whether for scientific or for culinary purposes. A

diary kept by the master diver Albert Falco, on *Conshelf I* testifies as well to feelings such as these: "The water is beginning to come into our grasp. I feel happy when I am alone with Claude [his diving and living companion]. The surface people with their photographic gear stir up the silt and make a real mud bath. I never like to leave a trace. They spoil the scenery for me. . . . We have actually witnessed the birth of hundreds of fish, and there are fish that escort us, always the same ones."

The experience of the men in *Conshelf III* and *Sealab II* have the ring of greater hardship. There were recurrent complaints of the numbing cold and the eerie darkness. The men were very much aware of being surrounded by the unknown and in the free dives from *Sealab II* there was apprehension, quite naturally, about not finding the base. The matter was not helped by the knowledge that should a man be lost the normal tendency to surface spelled certain death.

Although *Conshelf III* was more comfortable than *Sealab II*—probably because of the two-floor design of the former—in both the men had to rely on precooked food, since cooking fumes would have been toxic in the high-pressure helium atmosphere. For the same reason, smoking had to be prohibited.

There were no untoward aftereffects on the occupants of the undersea abodes recorded in the medical reports of either of these impressive saturation dives. There are discrepancies, however, between the two concerning work performance; some slowdown and reduced efficiency was registered by the Navy personnel, whereas the *Conshelf III* crew outperformed the average surface crew in their manipulations on a mockup of a submerged oil well. Since the men taking part in the two projects probably had comparable diving experience, the explanation of the difference may be in the tasks they were given to perform. For the Navy, these were standard tests devised by

medical men, whereas the French aquanauts were given more meaningful tasks to do.

Neither the purpose nor the dollar-and-cents cost of maintaining *Sealab II* and *Conshelf III* lends itself to calculations of cost in relation to benefit such as might be performed on deep-diving ventures backed by industry. It may be noted, however, that *Conshelf* significantly eliminated the use of a special and separate decompression capsule. Instead, the sphere was entered from the surface and went down with its ballast; when that was dropped, the sphere rose again and served as a decompression chamber for the aquanauts while it was moored to the pier at Monaco.

The need is certain to arise for temporary and highly mobile deep-sea abodes; and their prototype may well already have been invented by E. A. Link, whose name is associated with the Link Trainer. His SPID (short for Submersible, Portable, Inflatable Dwelling) is made of impermeable but flexible material, mounted on a pipe frame structure and restrained by webbing. Gas cylinders are attached to the frame, and inside are two bunks together with such equipment as a gas analyzer, a heater, a dehumidifier, CO_2 removal equipment, provisions, and water. On deck the SPID requires only 6 by 9 feet, and it is light enough to be lifted overboard by the booms or cranes of most research vessels. Once on the bottom, it can be inflated somewhat as though it were an underwater tent. One of Link's other inflatable structures, aptly named IGLOO, somewhat resembles a self-sufficient diving bell; it draws a supply of gas from tanks attached to its frame and affords a diver a working space on the bottom, eight feet in diameter, from which the water is excluded.

Link has to his credit the deepest saturation dive so far—two divers at 430 feet for two days—and his plans for further occupation of the sea floor continue. The Navy's *Sealab III* will be placed, a self-contained unit, at a depth of 450 feet. West-

inghouse Undersea Division, to name only one of the large companies involved in these ventures, has designed a small two-compartment submersible called the *Cachelot*, from the French word for the sperm whale, the deepest-diving mammal. Westinghouse has also developed a comfortable deck decompression chamber to be "mated when needed" to the submersible decompression chamber that goes up and down. Divers stay in the complex six or seven days and can go down to 450 feet. Much valuable salvaging has already been accomplished with this rig, and many submergence-system engineers are confident that soon men will work for eight hours a day at 200 meters or more for several days.

In spite, or indeed because, of these plans it may nevertheless be well to close this section with the words of caution used by Captain Mazzone, U.S.N., Dr. George Bond's associate in the *Sealab* ventures, to conclude his report "Human Physiology Aspects of Sealab II," in *Man's Extension into the Sea*:

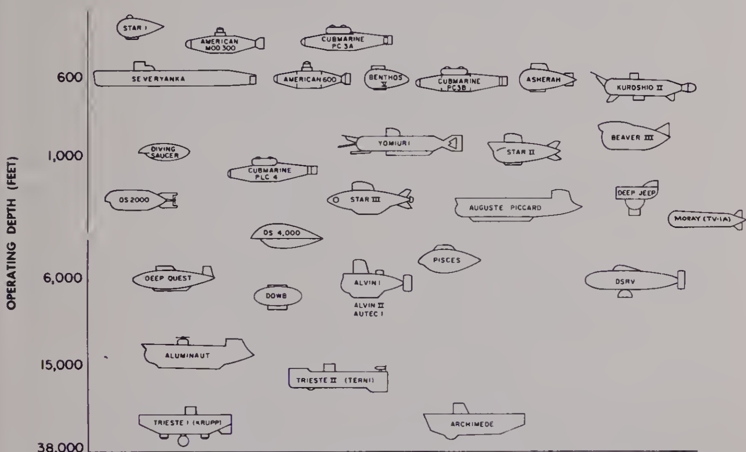
> Above all, one must exercise extreme reluctance in accepting superficial interpretations of results. Although for Sealab II all results were essentially within normal limits, it must be remembered that these normal limits have been stipulated for conditions on the surface, with a normal atmosphere, the design criteria established for the development of man.
>
> As man in the beginning came from the sea, the surface environment held the evolutionary design criteria—as we enter the program of retrogressive evolution, we must proceed with utmost care. We must set aside the urge to race to the bottom of the sea with reckless abandon, an approach which often prevails in programs of this magnitude, interest, and almost limitless military and economic potential.

Submersibles

Though some men will enter the sea through the open hatches of ever-deeper underwater stations, eventually perhaps to reach 300 meters (or close to a thousand feet), much

undersea work, both shallower and deeper, will be done from submersible craft. Some of these craft will be fashioned so that divers can indeed come and go from them; but others, especially those intended for very great depths, will maintain surface pressure and keep their occupants dry as well as relatively warm and comfortable (Fig. 19).

One such research submarine is the *Yomiuri,* a six-man midget submarine developed by Japanese scientists. Only its bright orange color betrays that it has nothing to do with the navies of the world, which select concealing rather than bright colors for their craft. Once when *Yomiuri* was about to go on a modest 400-foot dive in Tokyo Bay I was fortunate to join the party as an observer. While the four-man crew checked out ballast and equilibrium, I was already peering past the leather padding of the face-sized observation port in the bow. The



Marine Science Affairs—A Year of Transition. *The First Report of the President to the Congress on Marine Resources and Engineering Development, February, 1967, U.S. Government Printing Office*

Fig. 19. Diving capabilities of the world's research submersibles.

waves rocked us gently, and looking up I could see their ruffled, silvery undersides. Suddenly, in the very first few feet of descent, the wave motion ceased and plankton began to float upward past the window. The light assumed a greenish tinge, characteristic of fertile but fairly clear water. The green light outside gave way to blue-green and then to a blue that became increasingly deeper and more saturated. A squid floated by; frightened, it ejected its ink while it propelled itself backward with a strong jet from its siphons. A school of small fish scattered in all directions like large silvery flakes. Small crustaceans, worms and other zooplankters seemed to rise as the craft descended, permitting no more than tantalizing glimpses of the many different ways in which these little midwater animals dart and glide about.

Now the fathometer showed that the bottom was approaching and the water became a bit more turbid. The day was overcast, and the 1,000-watt searchlights were turned on when the sea floor came within range. The captain let the craft settle with an almost imperceptible thump, then raised it again to glide, not quite touching bottom, on a trip through an undersea animal garden. The silty sea floor seemed alive with the orange-hued feathery tentacles of burrowing worms that fanned the water for their particulate food. When the submarine approached, the tentacles were withdrawn into their tubes as though by some force from below, and small bright red sculpin-like fish darted about, frightened out of the small depressions where they had lain, each curled and nestled against a stone as though it craved contact with a hard surface.

Crabs, some of them six inches or more across, wandered about with raised claws in their slow deliberate walk, scavenging the ocean floor. Strange tracks in the mud led to snails a foot long, with coiled houses shaped like some triton's horn. Sponges of many different colors resembling stalked morels, mostly tinged with green or brown, weaved gently in a slow

current. Sea fans and sea candles of bizarre shapes, some perforated in a filigree-like pattern, at times stood almost as high as the little six-man submarine. These structures were covered with what appeared to be a fuzzy down, as the small colonial animals that had built them reached out tiny arms from their recesses, seeking microscopic food in the water surrounding them.

In places the bottom was covered by hundreds of starfish, orange colored with a red pattern, slowly moving about, some clumsily righting themselves after having accidentally turned themselves over. It can only be surmised that such animal aggregations, similar to those of the myriad crabs observed by Cousteau on a 1,000-foot diving saucer exploration in the Red Sea, either are temporary spawning assemblies or else exist because local currents have brought together dense concentrations of food. Waving from their stalks, several inches to a foot or more high, were colonies of white, yellow, and crimson sea anemones. Each colony was like a cluster of open flowers, though each of the delicate arms that compose the "petals" is round and moves under its own power, behaving in the fashion of dream flowers. Disturbed by the vibrations of the *Yomiuri*'s machinery, the anemones would close up their stalks still faintly moving in the slight current that prevailed.

Suddenly, out of the blue-black twilight beyond the cone of the searchlight there appeared a school of jacks, fish that are often encountered at the surface. Their scaled bodies glistened with bronze and silvery reflections and their eyes shone as they darted nervously about the strange intruder into their realm. They remained for a few minutes within the cone of light, trying but seemingly unable to escape, like a deer trapped between the car lights on a night highway. Some sharks also visited and circled the sub. One almost tried to peer in; then something frightened it, and with straining undulations of its long body it swam off quickly.

The difference in the shading of bottom-dwelling fish from that of swimmers is striking. The often-observed red color of the former is deceiving, since it is visible as red only to an observer equipped with artificial light that contains the red part of the spectrum. Very noticeable, though, are the darker and lighter streaks and blotches within the red, endowing the fish with a symmetrical grayish to brown-black dazzle pattern. The flatfish that occasionally rise out of the sand are even better camouflaged. Where there are pebbles, the pattern of brown-black and grayish-yellow spots on their backs approximates them in size; where there is sand, the pattern is more finely grained. In fact, flatfish are known to be able to see the size of the materials of their background and to adjust their color cells in such a manner that the over-all pattern blends with the substrate. When a flatfish moves, coming to lodge on ground with either larger or smaller fragments than the one it has left, it is able to adjust its pattern perfectly within a matter of minutes.

The patterning of a shark, and still more that of a jack, is in striking contrast to that of the bottom dwellers. Both are light below and dark gray or bluish above. A predator looking down on one of them might fail to detect it against the blue abyss, and the same would be true looking from below at its white belly against the silvery surface mirror. But even the sharks and the jacks are capable to some degree of adjusting their dark color cells; these expand or contract depending on whether the fish is swimming over a lighter or a darker bottom, and on whether the day is sunny or overcast.

The few special submarine research vehicles now in existence, aside from being small enough to navigate in and out of submarine canyons and other narrow places, are most of them equipped with mechanical claws with which objects can be plucked or lifted from the sea floor and dropped into an attached bag for emptying once the sub has surfaced. Con-

siderable skill is required to operate the claw, and a biologist with practice in manipulating similar devices from outside of radiation chambers easily has an advantage. A stalked sponge, for instance, must be plucked from as close to the ground as possible, and there must be an effort not to lose it, since if it slips from the pincers it is liable to be gone altogether. The sponge is of almost the same density as the water, and any slight current or motion that might fan it, such as that caused by the steel claw itself, will cause it to drift out of reach. Repeated attempts at grasping may destroy the delicate structure of a soft-bodied animal. A suction container, permitting such specimens to be brought ashore in the water that surrounds them when they were trapped, is superior for specimen collecting on the sea floor.

After several hours—which had seemed like minutes—aboard the *Yomiuri*, a radio message was received from the mother ship saying that the sea was becoming rough because of an approaching typhoon and the dive must be terminated. During those few hours I had been visibly aware of how many biological questions remained to be answered, even in this shallow submarine realm, just below the present range of free diving—not to mention those a geologist, for example, would have wished to raise. The extent of new knowledge that may come from systematic explorations of no more than the first thousand feet of the ocean is past imagining.

Many observation dives have already been made, most of them with the "soucoupe plongeante," or diving saucer, designed by Cousteau and Laban. The device, which is shaped like a scallop's shell and has a hatch on top that closes in the manner of a pressure cooker, has been in use for eight years and has made more than 400 dives, most often down to 300 meters (about 1,000 feet). Several times it has been flown across the Atlantic for the purpose. The saucer is a snug craft, with no waste space; its two occupants—the pilot and one observer—

lie inside and look out of two plexiglass viewports with windows fitted on a bevel so as to be self-sealing when the outside pressure increases. The craft is supplied with atmospheric air at surface pressure, to which oxygen is added as needed and from which the carbon dioxide is continuously being removed.

The saucer descends by adding two 55-pound weights, an operation that overcomes its small positive buoyancy while at the surface. At the desired depth—its range is 1,000 feet, though it has made some slightly deeper dives—one of the weights is dropped; when the craft is ready to surface, the second weight is released. Its progress upward or downward is at an angle and is accomplished by two water jets at the midline that can be rotated to produce a change in direction. Set to work at an angle of 180 degrees—that is, in reverse of each other—the jets cause the saucer to spin slowly like a giant top. It can also be made to pivot up and down, while hovering, by shifting some mercury ballast backward and forward in its hull. In performance it suggests some fantastic marine animal, especially as it rises from the ocean floor with its eye-like parts directed toward a scuba diver descending to meet it (Fig. 20).

The saucer's main attribute is its extreme maneuverability; it can be stopped no more than two feet short of a rock wall to allow its outside flash camera to take close-up photographs, and it can be used to explore submarine canyons and caves. It can also slowly sink or rise in mid-water, a feat that permitted a National Electronics Laboratory biologist, Eric G. Barham, to observe the animals that make up what is known as the deep scattering layers (or D.S.L., the customary abbreviation—see Chapter 4) and to follow them on their nightly migrations to the surface and then down again. First, the position of the animals was ascertained by means of echo sounding, and the saucer was directed to that level by underwater telephone. During the evening group after group of upward migrants passed the window and were identified. At dawn the craft

Westinghouse

Fig. 20. Aquanaut meets diving saucer.

followed the downward migrants until they began to exceed the saucer's diving range. The nature of the echo had led to the strong suspicion that it was caused by some form of gas inclusion, possibly a flotation device that allowed the animals to rise and sink with a minimum of muscular effort. The presence of such adjustable air floats was borne out clearly when it became apparent that lanternfishes, known to have a highly adjustable swim bladder, and siphonophores, a kind of jellyfish with breathing tubes, were prominent in the deep scattering layers. There were also squid and pelagic crabs, some of the latter apparently moving up and down by means of oil flotation, the exact nature of which is unknown but which appears to resemble that of a bathyscaphe.

Not all the animals in the D.S.L. were small, however. Among them, for instance, were compound tunicates (colonial

animals closely related to what may have been the ancestors of the vertebrates) from one to two feet long, and jellyfish in a ropy chain measuring sixty feet or more, with one- to two-foot tentacles which they let trail, the whole acting as a giant trap for plankton. Barham and other students of the deep scattering layers are not yet sure who eats whom in these assemblies of marine animals; but it is clear that at night large numbers of pelagic organisms come up to the surface to feed on what is produced by the photic zone of the sea.

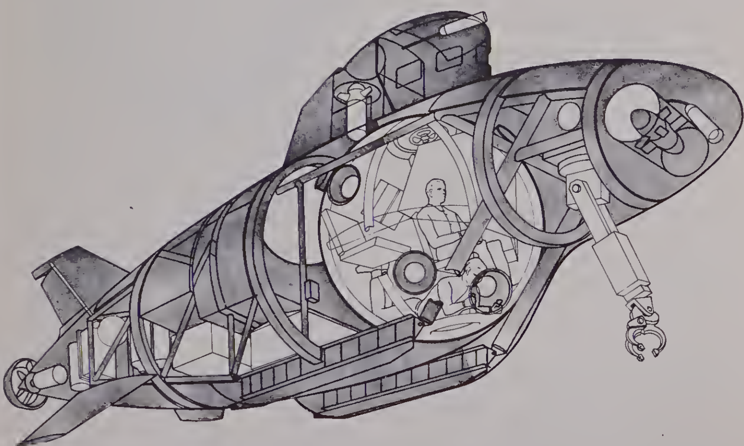
Up to now we have emphasized the biological observations; but diving vehicles are equally important, if not more so, for examining bottom sediments and other geological factors in the sea. Using mechanical claws, it is possible to take small cores with such uncanny precision that the layers of sediment can later be analyzed in detail. The exploration of submarine canyons has been undertaken in an effort to describe the currents in them and their relation to underwater sand and rock slides. The saucer has also been used for underwater sound work, and for experiments related to submarine rescue operations. It should be added that the average diving time of the saucer is four hours—though its oxygen supply lasts for twenty-four—and its top forward speed is one knot. It must be launched from a tender, but because of its convenient shape and small size it is easy to lift aboard a vessel. As already indicated, it can also be transported by air.

The diving saucer is the prototype of bigger, deeper-diving craft, based on the same general design, that are now in operation. One such craft is the *Deepstar,* a manned submersible produced by Westinghouse. It is also scallop-shaped, and it dives and rises by the adjustment of ballast, though it is moved by propellers rather than by water jets. The *Deepstar*'s crew of three travels in a spherical capsule that is contained within the scallop shell and protrudes from below, giving a slight bulge to the shape of the craft. The *Deepstar* can cruise from six to

twelve hours at a speed of three knots. A version equipped to reach 4,000 feet has made several test dives; one designed to reach 13,000 feet is now being designed, and another to aim for 20,000 feet, whose construction requires a specially tough and pressure-resistant hull of titanium-steel alloy, is planned for the next decade.

Other underwater research craft now under construction or in the planning stage are more nearly reminiscent of traditional submarines. One of these is *Star III*, made by General Dynamics Corporation (diving range 2,000 feet, diving time twelve hours, diving speed six knots, sea trials in 1966), whose design suggests the body of a shark—the recessed step where the observation ports are found resembling an underslung jaw and the conning tower with its entrance hatch resembling a high dorsal fin (Fig. 21).

The most impressive submarine research vehicle is the *Aluminaut*, built for the Reynolds Metal Company by General



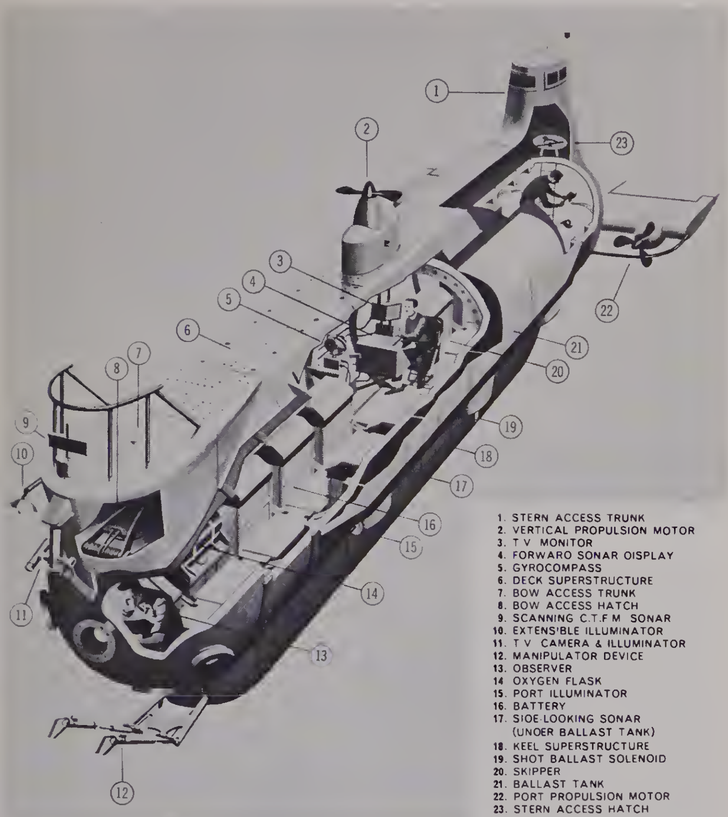
General Dynamics

Fig. 21. Planned 2,000-foot two-man research submersible, *Star III*.

Dynamics. By 1966 it was undergoing sea tests and had already been down several thousand feet. Driven by electric motors like a conventional submarine, it is equipped with viewing ports with cameras and a television receiver for scanning its surroundings, sonar operating in all directions, and a set of very sophisticated mechanical claws. To quote from a descriptive folder, "It is designed for scientific research, is fifty-one feet long, and has a six and one-half inch thick aluminum pressure hull. Its maximum operating depth of fifteen thousand feet will permit the *Aluminaut*'s one operator and two scientists to explore the bottom of three quarters of the world's oceans." By mid-1966 it had set the depth record for submarines at 6,250 feet (Fig. 22).

Currently planned or existing submersibles sacrifice the ability to travel long distances in favor of diving to great depths. On the other hand, prolonged dives at shallower depths may be of equal value to fact-finding expeditions. There is much to be learned, for instance, by remaining submerged long enough to watch the succession of events within the confines of an ocean current for several weeks. It would also be of great benefit to follow and observe such large fish as the tuna on their weeks-long travels in the tropical seas. A venture of this kind, to drift in the Gulf Stream, is planned with a new research submersible designed by Jacques Piccard, the originator of the *Mesoscaphe*, a submarine constructed for the Swiss National Exposition to provide tourist excursions under the waters of Lake Geneva. This luxury bus has already taken 38,000 people on a total of 850 dives to depths of more than 500 feet. It has forty windows and carries a large load and is probably the first of this kind of tourist recreation vehicle.

Since the purpose of staying submerged is best accomplished by nuclear-powered submarines—as the navies of the world well know—Dr. Donald Strasburg of the Honolulu Laboratory of the Bureau of Commercial Fisheries planned an atom-driven



Reynolds Metals Company

Fig. 22. *Aluminaut.*

submerged platform and laboratory to follow tuna and the related fast-swimming and fast-growing pelagic fish that are among the most important of the world's high seas animal resources. Its design, by engineers of General Dynamics, would equip this 163-foot research submarine to descend a thousand

feet below the surface; greater depths are not required to follow commercially important fish species. With space for a crew of twenty-four plus seven scientists, the craft could remain submerged for as long as six weeks on cruises with a 25,000-mile range. A 17-foot laboratory in the bow, a slightly smaller one in the stern, and an 8-foot forward observation sphere are part of the design. Seven television cameras and a host of oceanographic instruments—such as automatic water samplers, meters for temperature, oxygen, depth, and salinity gauges, echo sounders and hydrophones—would monitor the sub's surroundings. The stern laboratory would be equipped with a tube through which a trawl, plankton samplers, bottom samplers, fishing lines, and other gear could be launched en route.*

The nuclear power plant for this submarine is to be located within the hull; but for other, perhaps smaller, research submarines the nuclear power reactor may conceivably be placed beneath or above the hull. Such an arrangement would save space and have the additional advantages of allowing the surrounding sea water to cool the atomic engine and providing an effective shield against radiation hazards to the ship's personnel. Years would be required to construct such a craft, which would outdo Verne's *Nautilus,* and the question remains whether it will be built at all. Thus far the economic importance to the United States of its commercial fisheries has not led to anything comparable to the generous research support that other nations such as Russia and Japan, both of which are more dependent upon the fishing industry than we are, have provided for oceanographic investigations related to that industry. Though the utility of a nuclear research submarine for fisheries investigations is easily demonstrated, it may be the

* It is probably symptomatic of the United States attitude toward such matters that Dr. Strasburg has now joined the Electric Boat Company instead of trying, against very heavy odds indeed, to persuade the government of the richest country in the world to pioneer in the peaceful conquest of inner space as it is willing to do in outer space where military pay-offs are more likely.

glamour of becoming the first nation to build such an underwater vehicle, rather than its usefulness, that will lead to translating it from the drawing board to actuality.

The deepest-diving submarines are the bathyscaphes, in which men have visited even the very deepest ocean trenches. Initially designed by a Swiss and financed with Belgian capital, the bathyscaphe has been developed, modified, and improved by French, Italian, German, and American engineers. Bathyscaphes are mainly intended to go up and down, like a balloon (Fig. 23). In fact, they very much resemble aquatic balloons and their prototype was designed and built by Auguste Piccard, the man who first visited the stratosphere in a balloon,

U.S. Navy Deep Submergence Group

Fig. 23. The bathyscaphe *Trieste II*.

reaching a height of just over 54,000 feet. Like such high-altitude balloons, a bathyscaphe has a spherical observation chamber—a sphere being the shape best suited to withstand great pressures, either from without or from within.

Above the sphere is a soft-walled, compressible buoyancy chamber with roughly the form of a submarine's hull, which is filled with gasoline, a fluid lighter than water. Underneath are searchlights and ballast tanks, with metal weights. Spaces above the gasoline tanks can be flooded with water when the craft is ready to submerge. Like the ideally weighted scuba diver, who rises when he takes a deep breath and sinks when he exhales, the filling of the bathyscaphe's water tank makes the difference between sinking and staying afloat. It is made to rise again by releasing the metal ballast, which is held by means of an electromagnet.

The foregoing is no more than an outline of a bathyscaphe's working principles; it does justice neither to the ingenuity and skill that went into its construction nor to the many improvements that have been made in its design. Several new bathyscaphes were built and several older ones rebuilt after 1948, each with deeper and more effective diving capabilities than the last. One such craft, the *Trieste,* which had been bought by the Navy and furnished with an especially strong-walled pressure chamber, was piloted to a depth of 35,800 feet in the Challenger Deep off Guam in January, 1960. Unfortunately the Navy, in its hurry to bring off this feat ahead of the French—who were known to be working on a much-improved deep-diving bathyscaphe—had failed to equip the *Trieste* with an external flash camera. As a result, the two men in its observation sphere on that momentous dive, young Jacques Piccard and Navy Lieutenant Don Walsh, could not photograph the flatfish they found swimming over the very deepest bottom of the sea.

The chief task for which the bathyscaphe was designed—to move vertically through the water—has been accomplished.

Like a balloon in the air, it has not been designed to move any great distance under its own power once it reaches bottom, and it will eventually be replaced by more mobile deep-diving craft. In February, 1967, there existed reports on twenty-nine research submersibles (Fig. 19). Though some of them were still in construction, the number of nonmilitary underwater vehicles for the shallow ocean realm will increase rapidly during the next few years. The building of very deep-going craft will not proceed as speedily. There are fewer than a hand's count now in existence, and the building of more of them will likely have to await technological developments such as the capability to fashion glass, one of the best pressure-resistant materials, into the hulls of small research submarines.

The Sea from Above

Submersibles are nevertheless being built as fast as engineers can cope with the special problems posed by the various scientific tasks for which they are intended. Their importance would be assessed at future Oceanographic Congresses. Such, at any rate, was the opinion of R. H. Charlier when he reported in *Science* for September 16, 1966, on the Oceanographic Congress that took place in Moscow in June of that year. No less than the step beneath the sea, the step into space also holds great promise for oceanographic research; these gains also are to be documented at future international gatherings.

Scott Carpenter, the former astronaut turned aquanaut, has already seen the sea from both high up and down below. In the submerged oceanographic stations of the present and the future, the observers will be in search of detailed local information, while satellites and manned orbital laboratories will give a synoptic view of the sea. For instance, John Glenn, Carpenter's orbiting colleague, reported seeing the Gulf Stream—an observation he was able to make because the current's water mass differs in thermal and reflective properties

from the sea through which it flows, leaving its own optical "signature," as it were. But visible light is only a small part of the radiation naturally reflected from any surface of the globe. Beyond the range of human eyes but within that of sensitive instruments is the infrared band of the spectrum. The degree to which infrared is reflected by water varies with the temperature. These variations can be registered from the air with thermocouples, and ocean temperatures thus can be taken from above. This process, known as infrared remote sensing, is valuable mainly as a way to measure reflection and thus to arrive at temperature differences in space and time. This is as contrasted to absolute measurements, what the sensing engineers call "ground truth"—that is, measurements obtained on the spot. From the air infrared thermometers not only register the reflection by the water surface but also are affected by the water vapor above, especially in the thin transition layer between water and air. Consequently some corrections have to be applied for the conversion of infrared into mercury-thermometer temperatures. Nevertheless, variations of temperature are accurately reflected down to one degree Fahrenheit or less, and surface isotherms (lines of equal temperature) can be plotted with the help of these instruments.

Scientists at the Sandy Hook Marine Laboratory have been using infrared thermometers to make temperature surveys from the air since 1962. These scientists fly with the Coast Guard, covering 20,000 square miles of the waters above the North American continental shelf, from Cape Cod to Delaware, and accomplishing their mission in three days of five hours' flying time. A dozen boats in a dozen days could not have done as well. Whales, sharks, and dark patches below the surface that turned out to be schools of mackerel have been spotted on these flights. A comparison with the temperature records revealed, for instance, that the mackerel congregated during May in waters where the temperature was between 50 and 52

degrees Fahrenheit and practically nowhere else—demonstrating once again that temperature is a strong factor in the distribution and behavior of marine animals. The advantage of the correlation is obvious, if for no other reason than its use in predicting the prevalence of schools of fish over wide areas.

Infrared earth sensors will surely become standard equipment for satellites, since far more is to be gained from them than from the measurement of sea temperatures. Icebergs and crevasses in sea ice show up in infrared sensing, as do rivers that are warmer or colder than the sea into which they flow. By the same means, zones of upwelling can be delineated, especially their variations by season or over longer periods.

Instruments that are carried on aircraft, on space platforms, or by satellites can scan the earth and the sea from the ultraviolet band through the range of visible light and into the infrared. Aside from pictures, it will be possible by the same means to record what are called multispectral signatures. In order to develop these signatures—as specific to a particular plant as its odor—one must record from a code only partially visible to the human eye. First one photographs a stand of such plants, say of corn and oats, on different films sensitive to several different wavelengths. It will then be found that in a line connecting points of relative brightness in each of these wavelengths the shapes produced by the two grains differ sufficiently to allow a trained interpreter to tell which predominated in a particular part of the globe, provided multispectral scanning data were to be available on a suitably large scale.

Multispectral signatures of plants are possible because each species has its own characteristic distribution of pigments, such as chlorophyll and carotene, its own special cell wall structures, and its own relative hairiness, thickness of leaf, and so on. Algae, being plants, obey the same laws of genetics and evolution as corn and oats, but their cells contain an even greater variety of pigments (see pp. 203–11). It is therefore not

mere fancy to expect the eventual development of remote scanners that can tell us not only where algae grow or float but also what kind they are and that concentrations of a noxious species such as those that cause the lethal "red tides" will one day be mapped, perhaps even early enough to be nipped in the bud.

Promising as oceanography from the stratosphere or from space may appear—and we have mentioned only a few of the applications currently envisaged—one serious obstacle remains: at sea the sky is often overcast, making images or records temporarily unfeasible. For this reason manned or unmanned satellites will probably assume their greatest importance as radio relay stations for weather and oceanographic information that is gathered by ships or automatically recorded from strategically placed or floating buoys. For large ocean areas that are not crossed by ships, the lack of oceanographic data leaves vast gaps in our knowledge of the sea as a dynamic system. To this problem automatic recording buoys that either store or broadcast the information they gather are the obvious solution, and orbiting space vehicles the obvious relay devices.

The Seattle Laboratory of the Bureau of Commercial Fisheries has maintained radio contact for three months with free-floating telemetering buoys in the northeastern Pacific and has even recovered these buoys at the end of the period. Engineers for the Office of Naval Research have designed a buoy that can gather simultaneously as many as a hundred different pieces of information which it is able to store for over a year. Also it can transmit data gathered during the preceding twenty-four hours when queried. Buoys need not float on the surface, but can also be submerged. Such buoys would be equipped with an instrument package that could be retrieved on command; others could drift, perhaps after being dropped from an airplane, and might be triangulated by radar or other means.

In the long run buoys will be cheaper than ships and,

--upled with satellites, will work in weather forecasting and as aids to navigation, as well as in oceanography (Fig. 24). In contrast to the remote scanning that might be done from above, they will produce data with "ground truth"; in fact, by means of wires and lines they will record from as far down as 200 meters, yet in contrast to earlier shipboard observations, by means of satellite communication they will make information available almost simultaneously from vast expanses of the sea.

Not all the satellite-related buoys need be man-made, though. William E. Schevill, the Harvard University expert on marine mammals, remarked during a conversation about the applications of satellites or high-flying aircraft to the study of whales, that these latter were buoys that had already been launched, but that were "hard to hold during instrument mounting." The ideal whale tag containing a radio transmitter would have to be small and hydrodynamically perfect, since whales swim fast. Every transmitter fixed to a whale by means of a harpoon would be required to have its own frequency, so as to permit individual whales to be distinguished. Other possibilities might include transmitters that would respond only to the frequent sweep beam of radar, or that would both signal the presence of a whale, and thus indicate its route, and also measure, code, and transmit its body temperature, rate of heartbeat, depth of dive, and other biological variables. Surely it would then be possible to learn about whales what cannot be deduced from hunting them and examining their carcasses.

Eventually there will be orbiting observatories, some perhaps as early as 1975, to be manned occasionally by oceanographers. Later graduate students in oceanography will do field work from space. Orbiting oceanographers will no doubt work closely with meteorologists. Although they will perhaps deal mainly with the effects of the oceans upon clouds and the weather, they may also be called upon to detect hitherto unknown ocean phenomena such as are observable only from

Woods Hole Oceanographic Institution

Fig. 24. Radio telemetering buoy being lowered from the Woods Hole Oceanographic Institution research vessel *Chain*. This instrument may be either anchored or drifting. Its purpose is to pick up electronically sound signals emitted by the ship and reflected from the ocean floor and the subsurface structure of the earth's crust many meters below the floor. This information is transmitted to the ship by radio.

those heights. Although their work will be aided by batteries of sensors that go far beyond the oceanographers' range of vision, these devices will supplement rather than replace the men themselves. For men, taken weight for weight and volume for volume, are and will remain the best circuit monitors and error-correcting devices available, and "programmed" to boot, as no computer can be, to turn the unanticipated disadvantage into a gain.

3

Gathering the Harvest

EVEN IF the report of Alexander's diving bell is true, man was a fisherman long before he became a diver. Remains of fishing tools dating to several millennia before Christ suggest that fishing is at least as old as hunting. And from the time primitive men first applied husbandry to the animal and plant products of the land the labor of the fisherman has stood in sharp contrast to that of the rudest farmer. A Yarmouth sea chantey illustrates this difference:

> The farmer has his rent to pay.
>   Haul, you joskins,* haul.
> And seed to buy, I've heard him say.
>   Haul, you joskins, haul.
> But we who plough the North Sea deep
> Though never sowing, always reap,
> The harvest which to all is free,
> And Gorleston light is home for me.
>   Haul, you joskins, haul.

In some places today the hunt is conducted with electronic fish-detecting devices or with scouting planes, for example, in whaling and tuna fishing. The quarry may be pumped into the hold with a continuous stream of water or an electric current may be used to attract the fish over a short distance and then to stun them in order to bring them aboard more easily. Yet even

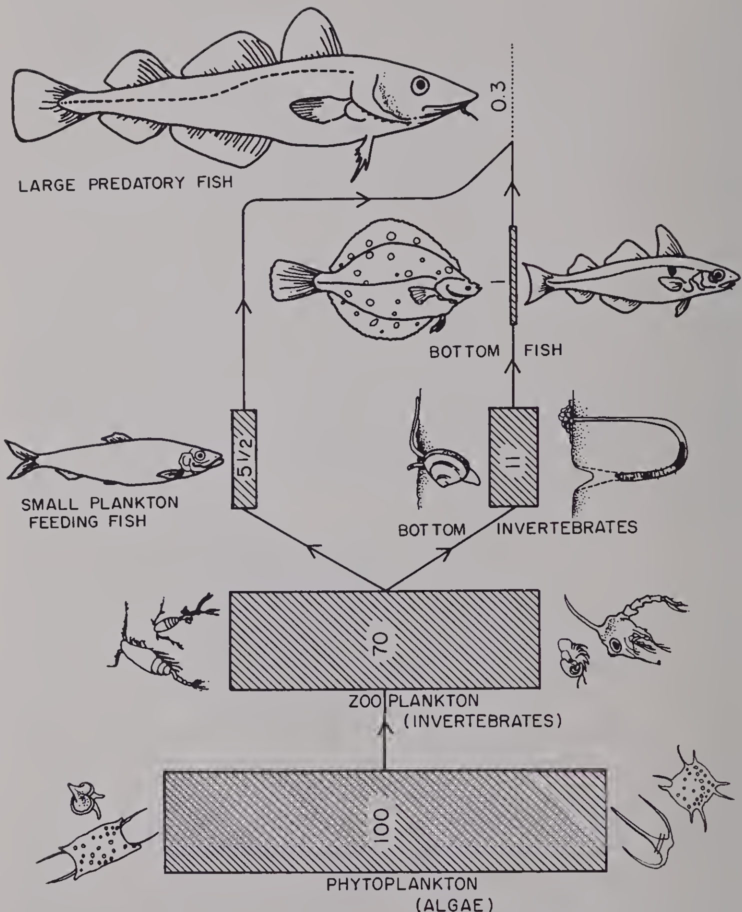
* In Norfolk terms joskins are part-time fishermen who farm in the summer and join the herring fleet during the winter.

in the mid-twentieth century the greater part of the total annual catch of fish and other aquatic animals, amounting to nearly 60 million metric tons (or about 130 billion pounds), is still taken in the age-old way, with nets and hooks.

Man breeds domesticated land animals for several desired characteristics, but he has yet to tame the creatures of the sea. What he has taken and is now taking from the oceans is nature's own surplus; often it may be more than that. Only in the last century—which is truly but yesterday in recorded history—did it occur to scientists and administrators in charge of men and fish to doubt that the sea was inexhaustible. Previously there had been no such doubt because the sea appeared so vast and because it was known that many fish laid millions of eggs. It is now known, however, that most of the larvae that develop from those eggs die, and in some areas of the oceans that are heavily fished, such as the North Sea, signs of depletion have been noted.

In contrast to land animals such as cattle and sheep, which are plant eaters, the fish we prefer to catch are meat eaters. Some, such as tuna, live on smaller fish and squid, which in turn live on animal plankton, which in turn graze the sea for plant plankton or floating algae. Even the herring, a fish with a complicated food cycle, is two or possibly three steps removed from the plant sources that are the true pasture of the sea. Each step removed from that source entails a loss of from 80 to 90 percent of the substance, and therefore the energy, of the previous stage. The difference is simply used up in swimming, breathing, and the business of staying alive. Thus the meal we eventually make of fish and shellfish represents only a minute fraction of the energy that was used up in the steps that separate it from the algae in the sea (Fig. 25).

Anyone interested in calculating how many calories of sunlight and how many tons of either algae or grass are needed, respectively, to produce a ton of tuna or of beef will find some



Redrawn after Dr. G. P. Baerends, 1961

Fig. 25. Simple marine food chain. The numbers and the sizes of the boxes represent the respective weights of the organisms on any one level (zooplankton does so well because it, apparently, feeds also on more minute organisms than the algae represented here).

figures in Professor Georg Borgstrom's sobering book, *The Hungry Planet.* Professor Borgstrom notes that the total aquatic catch in 1960 required as its plant base between sixty and seventy times the weight of the world's wheat crop and engaged no less than 15 percent of the total of the photosynthesis that took place in all the world's oceans. Thus every year almost a fifth of all the algae in the sea are already being used up in feeding us—evidence that the living resources of the sea are indeed far from limitless.

In some places we are running out of land on which to grow food, and it has been suggested that we should turn to the sea. True, the Americas are far from this predicament as yet, but they share the ocean that bathes their shores with continents with far less unused land than they. Moreover, the sea and whatever lives in it belong not to one nation but to all. It is thus in order for us to examine some facts about life in the sea, based in part on previous sections to discover where sea life abounds and where it is scarce, before going on to such things as the past and present scramble for food from the oceans, the dispute over fishing rights and the law of the sea. The prospects for the harvest of plankton as a crop and for the culture and domestication of marine animals must all be examined before making any appraisal of what the ultimate harvest might be.

The Fertility of the Sea

Most of the packages that arrive at the Unesco International Oceanographic Center at Charlottenlund Castle in Denmark are labeled "Radioactive Materials." They contain series of small disks which are usually tinged with green as a result of having water with phytoplankton (floating algae) filtered through them. The plankton will have been inoculated with C_{14}, a weakly radioactive isotope of ordinary carbon, by a

process that permits the calculation of how much carbon is gathered into the protoplasm of the algae within a specified time.

The Center was set up by Professor Steemann Neilsen, the inventor of the carbon 14 technique for measuring primary production in the sea, and is especially intended to serve small oceanographic laboratories, mainly in newly developing countries. Through the Center such laboratories are furnished with small ampoules containing specified amounts of C_{14} in solution, to be injected into plankton samples—a procedure, incidentally, that assures standardization, and therefore comparable results from many different sampling stations in the sea.

In field operations the technique is a simple one, relying on the basic facts of photosynthesis: that green plants take in inorganic carbon and transform or assimilate it into the carbon compounds of their protoplasm—plus a few well-tested assumptions. Ordinary carbon and carbon 14 are used by the algae at almost the same rate; a minor correction factor for the slightly heavier carbon 14 can be applied to the final calculations. A water sample of standard volume, containing phytoplankton, is drawn from the desired depth, its CO_2 content is determined by simple, standard chemical tests, and the contents of a sealed ampoule, including a known amount of C_{14} carbon dioxide, are added.

In a glass container the inoculated sample may be returned to the depth from which it was taken by suspending it from a buoy; or it may be placed in a water bath on deck and allowed to carry on photosynthesis. If the water sample to be treated on board has come from greater depth, the surface light is subdued with neutral-density filters and the water bath is cooled to simulate the proper temperature conditions at sampling depth. After a few hours—usually four—the water is filtered through millipore collodion disks which retain all algae. The filters are then dried and their radioactivity is determined.

Inasmuch as C_{14} has a half-life of 5,500 years, speed is not of the essence.*

At the beginning of the experiment there is in each bottle a known ratio of C_{14} carbon dioxide to total carbon dioxide, as determined by an initial chemical test. Since normal and radioactive CO_2 are used by plants at virtually the same rate, the intensity of radiation on the filter—proportionate to the number of clicks in the counter—allows the calculation of all the carbon atoms used and thus of the amount of photosynthesis.

The method described here, though only in its bare essentials, measures gross primary production—that is, the excess of photosynthesis over respiration. It lends itself well to locating the depth in various parts of the ocean at which photosynthesis still proceeds, and to comparing relative fertilities. It also furnishes clues about the distribution of nutrients, since differential rates of carbon fixation in waters of similar transparency and temperature will most probably be due to a difference in nutrient content, perhaps to a lack either of essential or trace elements. Although the technique became known only in 1952, it has superseded other, cruder methods because it is less prone to error. It has already furnished a wealth of information on the potentials of the sea that may eventually be applied to human welfare.

The units used in expressing carbon fixation are grams (or milligrams) per day of carbon assimilated by the plant in a water column of a certain depth under a surface area of one square meter (about one square yard). This is abbreviated as C/m^2 day. Comparison of many thousands of C_{14} measurements in many aquatic environments were made with due consideration of the carbon compounds used by the plant for respiration, measured in the dark while photosynthesis does not interfere, and of the metabolism of the ubiquitous bacteria.

* The half-life of an isotope is the time span for the decay of 50 percent of its radioactivity.

The figures so obtained permitted estimates of fertility in many ocean areas at different seasons, as well as important comparisons with the fertility of the land.

Some surprising facts emerged from these investigations. "The open sea is a desert compared to moderately fertile land," according to the Woods Hole scientist John Ryther—who is probably the most experienced American biological oceanographer in matters of primary productivity. He goes on to say that even fertile littoral zones lag behind the land in their potential to support plant growth. The reason for this discrepancy is simple, namely, that rich fertile soil contains up to 0.5 percent nitrogen, whereas rich (unpolluted) sea water contains only 0.00005 percent of the same essential element. (The distribution of another essential element, phosphorus, generally corresponds to nitrogen.) Topsoil that extends several feet down can produce, under optimal conditions, in excess of 200 tons of dry organic matter per acre per year; the richest zones in the open ocean yield at best only a tenth of this amount.

Littoral areas where there are attached plants, such as kelp beds and coral reefs, do better. In some of these the rates of carbon fixation and therefore of the total fertility approach that of land. Ryther and others have estimated that attached marine plants contribute a substantial percentage of total oceanic productivity—an especially noteworthy fact if it is remembered that they cover only about 0.1 percent of the total surface of the sea.

Water color is a good indicator of relative fertility. That, by and large, the bluer the sea the more barren it is has been known to fishermen from time immemorial. Carbon 14 measurements of photosynthesis have borne this out and have provided exact figures. Parts of the blue Mediterranean and the almost inky Sargasso Sea, for instance, had assimilation rates of around 0.05 g C/m^2 day, whereas the corresponding figures for

temperate and colder seas were ten times or more higher. By the same token, a sewage oxidation pond that is about one meter (3 feet) deep has the same rate of photosynthesis as a water column 100 meters deep and of the same area in the Sargasso Sea. It is therefore not surprising that all the floating and attached marine algae in existence at any one time are believed—though the estimates are still inexact—to store in their protoplasm only twice as much energy, at best, as all existing land plants, in spite of the 3-to-1 preponderance of water over land throughout the globe.

The reason for these differences in ocean fertility is the relative availability of nutrient materials. In tropical seas the water is heated throughout the year, so as to produce a layer of warm water deeper than that penetrated by sufficient light for plants to grow. Warm water, even when it is highly saline, is less dense than cold. It floats on the surface, and the difference in density between the two layers is great enough so that no wind, not even the strongest tropical storm, can mix them.

In tropical seas the phytoplankton grow fast and use the nutrients in the surface waters. The algae are eaten by the zooplankton, which are devoured in turn by larger invertebrates and by fishes. In the normal course of events these larger organisms eventually die and sink to the bottom. Even though the dead organisms in the surface layer, known as the euphotic zone (from the Greek *eu*—good, and *photic*—light-containing, hence "well-lit"), are immediately attacked by bacteria—a process that retards the loss of matter from the upper waters because the bacteria themselves are eaten on the spot—the surface waters nevertheless become depleted of elements most important to living matter, and in some regions of essential minor elements such as iron or cobalt as well.

In temperate seas the upper warm water layer forms only during the warm season, and below it a layer of rapidly changing temperature and density, known as the thermocline,

breaks down when the air overhead becomes considerably colder than the sea. At such times the surface waters and those beneath are of approximately the same density, so that they mix, permitting the nutrients locked in the deeper layers to become available to the algae. In the spring, when ample light again prevails, algae and diatoms begin to reproduce, setting the stage for a myriad zooplankton to graze and multiply, and for fish to gorge themselves and produce young.

Beginning in the fall, the fertility declines. The measurement of photosynthesis made in January in the North Atlantic off New York turned out to be four times lower than in March and forty times lower than in May. In June photosynthesis declined again, owing to the establishment of a thermocline which for a time sealed off the surface waters from those below, temporarily producing conditions comparable to those that are constant in the tropics. In September and October, when the thermocline began to break down, a second, smaller "bloom" of algae was observed, with photosynthetic rates nearly half of those in the spring. In November photosynthesis was curbed once more by clouds and fog that shut out much of the light.

Algae, especially those that float, are clearly indispensable to the pyramid of ocean life. They in turn depend on the presence of nutrients and light without which there would be virtually no life in the sea. But the distribution of these two factors is not uniform. As we have seen, there are barren areas and there are fertile ones which are visited by men in ships who come to reap the benefits. Of the fishing tools now available, few reach depths greater than a few hundred feet. It must be remembered, of course, that the harvest from the darker regions below is not likely to be large. The team of divers who recently inhabited *Conshelf III* at 328 feet below the surface demonstrated, as one of their experiments, that it is possible to grow algae in illuminated boxes despite the surrounding dark and cold, provided the light is strong enough. But even though the experiment proved that algae can be grown in such circum-

stances, the question remains whether the expense of constructing the machinery and of supplying the power for thus extending the photosynthetic zone of the ocean would not be prohibitive.

The fundamental constituents of ocean fertility are nitrogen and phosphorus compounds, including those locked up in the dissolved organic material in the surface layers. These materials are of great importance in the nutrition of all floating organisms and are most prevalent in the zones of upwelling. Such zones are found on the western coasts of the continents, as, for example, in the Humboldt Current off Peru, in the Antarctic, and seasonally, at the time of overturn, in cold, shallow waters such as the North Sea and the area of the Newfoundland Banks. Fertile regions also occur where large rivers, such as the Amazon and the Mekong, flow into the sea.

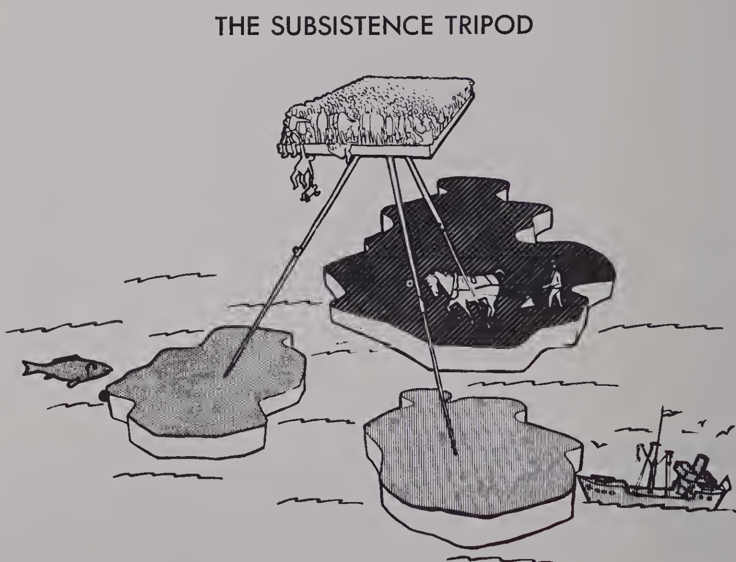
The regions of high oceanic fertility, and thus the best fishing grounds, do not always occur near populous regions on land. Some, including the North Sea, lie near population centers and have been exploited for a long time. The existence of others, for example, the grounds off Peru, have been predicted from a knowledge of oceanography and have only recently been verified. Still others, including some yet to be tapped, have had to await the perfecting of far-ranging factory ships (Fig. 30).

Fishing Regions of the World

Before 1950 there was virtually no fishing in the Southern Hemisphere; the oceans north of the equator supplied over 95 percent of the world's supply. Fishermen generally have stayed close to home, with such notable exceptions as the British, the Portuguese, and the French, who have long participated in the Newfoundland cod fisheries, and the Yankee whalers, who once combed all the seas for their quarry. Following World War II, however, the technologically advanced nations spread

so rapidly over hitherto unexploited reaches of the sea that the southern oceans now supply about 35 percent of the total world catch. Between 1952 and 1962 that catch was approximately doubled, and in so doing it has kept ahead of the increase in world population, including even that of such rapidly growing regions as Central America, where new mouths to feed are being added at a rate of 3.5 percent a year.

For many nations—the United States is not among them—taking fish from the sea is absolutely essential because there is not enough land to grow the plants necessary to yield a supply of protein in the form of livestock (Fig. 26). But even in North



G. Borgstrom

Fig. 26. The nutritional base of an imaginary, highly populated country: agriculture, fisheries, and imported foods (ideally bought with export goods).

America, which has an agricultural surplus, a 22 percent increase in dairy production would be required if the proteins now supplied by fish for the feeding of other animals were to be replaced with skim milk. Few people are aware of the degree to which the U.S. production of broilers relies on fish meal (Fig. 27). In other countries the contribution of fish to the protein intake of the people is much more spectacular; for example, a tilled area almost twice as large as Japan would be needed to replace that country's fish harvest with land-based animal proteins (Fig. 28), and for Egypt the equivalent figure would be 50 percent of the total area. Even cattle-raising countries like Argentina and Australia rely upon fish to some degree.

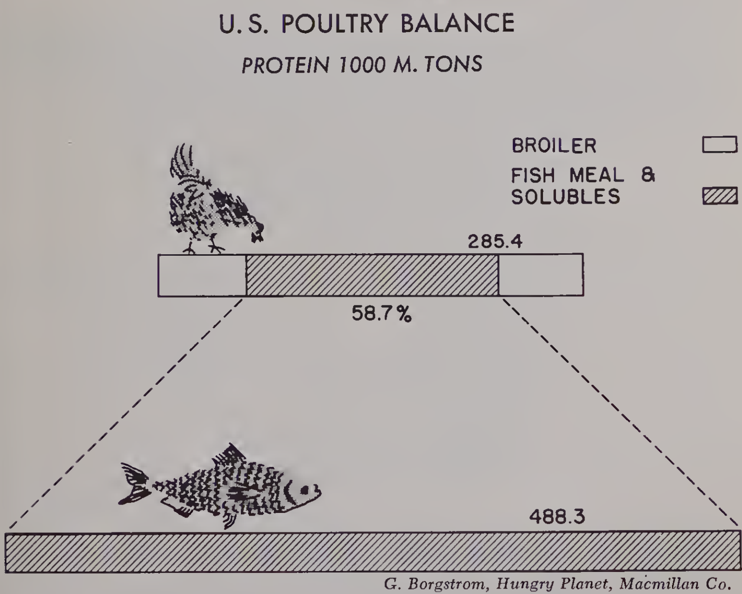
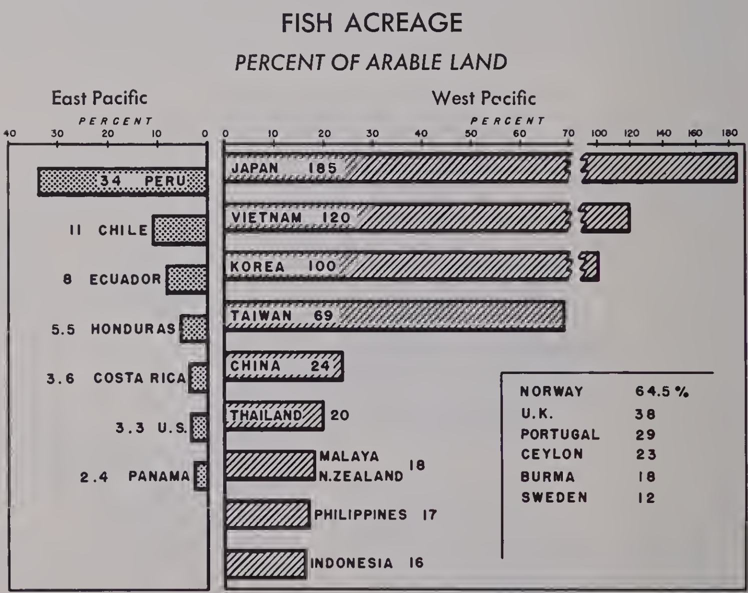


Fig. 27. The role of fish meal in U.S. poultry production. Note that more than half the feed of broiler chickens comes from the sea.

In view of these considerations it might seem reassuring that the world fish harvest has gone up so rapidly of late and that there appears to be a promise of further expansion in the harvest of sea proteins to assuage the hunger of the world. Yet a more careful look, to learn just where the growth has occurred, and whose diet has been improved thereby, does not disclose a very rosy prospect.

Professor Georg Borgstrom, the nutrition expert who has already been quoted, stresses that during the past decade three events have dominated the world's fisheries. The first is the



G. Borgstrom, Hungry Planet, Macmillan Co.

Fig. 28. The bar graphs give in percents of arable land the acreage necessary to produce what the countries now obtain from the sea. In the case of Japan, for example, almost two more Japans would be needed if that nation stopped fishing.

emergence of a great power, the Soviet Union, as a maritime empire with fishing fleets in all the oceans. The second is the achievement of Japan in having equaled—and even surpassed—her prewar catches with fishing operations that also have spread all over the world, as well as in giving technical aid in fisheries to many developing countries. Indeed, that aid has been on a scale that may well rival the fisheries advisory activities of FAO, the Food and Agriculture Organization of the United Nations, and Japanese transshipment ports and fishing bases literally encircle the globe.

The third major event has been the increase everywhere in the manufacture of fish meal, and the especially noticeable emergence of Peru, in barely five years, as the world's largest producer of fish meal. Peru, although not traditionally a fishing nation, now holds first place in global fish landings. This development is due, of course, to the upwelling waters of the Humboldt Current, hitherto scarcely tapped—and it is a foreshadowing of like events along the coast of West Africa, where the Benguela Current produces vast schools of small plankton-eating fishes that are the base for making fish meal.

The Soviet catches have helped to bring the diet of the 230 million Russians to a nutritional level approaching that of other parts of the Western world. Japan needs much of her catch for her own population, but sells the rest, consisting of tuna, largely to customers in America and Europe. In America and Western Europe billions of pounds of fish meal also go to feed factory-produced chickens or are added to hog rations. The oil that is a by-product of rendering fish meal goes, among other countries, into margarine in Holland, West Germany, and Great Britain.

This aspect of world trade clearly shows that proteins from the sea now flow from regions where hunger is rampant to those of abundance. Moreover, a great quantity of the fish caught are not utilized directly as food but go into feed for

land animals. This practice is wasteful because it lengthens the food chain by one more extra link, since only 15 percent, at best, of the input reappears as meat that can be used; the rest is burned and excreted as a result of the various life functions of the pig or chick that is fed on fish meal. Eventually, mankind will consume directly most of the fish that are caught without interposing this further wasteful link between the source and the ultimate consumer of the protein. To this end, experiments are under way in several countries, including the United States, for making palatable fish concentrates. Even when those are on the market, hundreds of millions of persons will still rely on more traditional fishery products as a not always sufficient daily ration of animal protein. The ways in which these products are harvested, and how the methods might be improved, will be the topic of the section that follows.

Catching Fish

The net and the fishhook are among man's earliest inventions, and in character they have changed very little throughout the millennia of human history. As soon as plant fibers began to be spun and knots to be devised, fishnets were possible. They existed in Sumer and in ancient China, and are probably far older than the arts of writing and carving. Such nets are now made of nylon with many times the strength of plant fibers in a strand of the same thickness, and they are pulled by powerful vessels; but though they are buoyed with plastic or glass floats more durable than those traditionally made of balsa or other light wood, the fish are surrounded or trapped and are entangled by their gill covers exactly as they have been from the very earliest times.

Primitive men probably clubbed or speared fish before they began using hook and line to catch them. Also probably more ancient than the hook are the weirs set in the paths of migrat-

ing fish and the arrows that are shot at pike and similar large predators as they bask in the shallows. Much conjecture goes into any reconstruction of prehistoric devices, but according to William Radcliffe in his learned treatise *Fishing from the Earliest Times*, well-fashioned copper hooks had made their appearance at least by 2800 B.C., or the beginning of the first dynasty in Egypt. Hooks of stone or bone—even of human bone—(and probably of wood, though they have vanished) clearly antedate hooks made of metal (Fig. 29) and may well go back ten thousand years or more. The early stone hooks were barbless, with an inner curvature produced by drilling out a circle, and were finely fashioned by chipping, filing, or possibly by sawing. Making a hook in this manner left a point below the tip, which may well accidentally have given rise to the barb. If so, the advantage must have become obvious to the early craftsman once he had caught a fish with it.

Still earlier than hooks are gorges—small bone rods, such as have been found in the caves of the Dordogne in France, inhabited by paleolithic men 30,000 to 40,000 years ago. A gorge is pointed at both ends, and has been fashioned by chipping, with a groove or notch in the center, to which a line is attached. Such fishing tools, some made of shell and others of wood, are still used today in some places. They are baited with minnows or other small fish in such a way as to be swallowed head on—whereupon the line is pulled taut and the rod is wedged sideways in the predatory fish's craw. Some gorges are straight; others are slightly bent. In either event, not much imagination is required to see how this most primitive fishing tool could have become the precursor of the stainless steel hook of today.

In the nineteenth century the uses of hooks and of their fishing counterparts, the nets, were greatly augmented, first by the harnessing of steam and shortly after that by the invention of the internal-combustion engine. Mariners could now navi-

G. Forsythe

Fig. 29. Ancient Roman fisherman baiting his hook, probably an early type made of metal. (Mosaic from Sabratha.)

gate at will, rather than submit to the vagaries of the wind, and there was a source of power to pull the lines and haul the nets aboard their ships such as they had previously never dreamed of. Whether or not the technological and scientific revolutions are to be separated from their industrial ancestor, there is no doubt that they have meant an extension of human senses. Such instruments are the radio telescope and the electron microscopes, or the radio direction finders that enable skippers to navigate in fog, and the echo sounders that locate schools of fish. Nevertheless, the very act of catching fish still relies on hooks and on various kind of nets—the latter accounting by bulk for almost three fourths of the fish that are commercially caught today. Neither such primitive fishing tools as harpoons, traps, and weirs nor such ultramodern ones as pumps coupled with electrical attracting devices play more than a very minor role.

During a year's fishing, a Polynesian may bring in a thousand pounds of fresh fish. Aboard a modern Russian trawler the share of the total catch by a single member of the crew may be three or four hundred times this amount. The discrepancy is less a matter of skill than of the nature of the fishing vessel and its equipment—such as power winches.

The efficiency of such a vessel is not due to any single technological advance. The size of the ship and the power of its engine are important; so is radar, which enables the navigator to find a position and hold a course in fog and storms. Fish finders based on the reflection of sound and ultrasound pulses from the bodies of the animals, notably as reflected by swim bladders, have transformed the nature of fishing from a matter of luck to a trade in which the skipper must have technological training. The spotting of schools of fish from airplanes now also plays its part in making the hunt more efficient than ever before. Less spectacular innovations in the process of fishing itself have recently done much to streamline and mechanize

the once-backbreaking task of hauling and tending the nets. Two of these innovations are the power block, used to pull seines, and the practice of trawling through the stern rather than over the sides of the vessel. Both are worth describing in some detail.

Among the nets in common use are several kinds that are moved to catch the fish, rather than simply waiting for the fish to bite or to enter the net by accident. These active nets, most of which are now made of nylon, include the various seines and trawls, some of which are gigantic. The seines used to gather Pacific herring are 400 fathoms long (2,400 feet); those for netting tuna extend over three quarters of a mile and are 50 fathoms deep. These are purse seines—that is, they are made with a drawstring—actually a rope—at the bottom. When the school of fish has been surrounded and the ends of the net have come together, pulling the purse line holds the fish in a large pocket of netting, which is pulled progressively smaller until the thrashing and squirming quarry can be netted or pumped into the hold of the ship. The labor of closing so large a seine and of gathering the purse required many hands, and was backbreaking work. Today the labor has become much less for the men aboard boats equipped with a power block. This seemingly simple device was invented by Mario Puretic, a sardine and tuna fisherman of San Pedro, California. Its basic operating principle is to pass the entire seine through a grooved pulley, or sheave, whose self-propelled roller has a V-shaped profile, hung overhead from a boom and rotating freely. The roller is equipped with cleats that grip the net and is driven by a small compressed-air pump. As the net rolls through the V it comes aboard in such a way that it folds down from above, thus doing away with the heavy resistance involved in pulling it up hand over hand.

Under certain circumstances a school may escape from a seine even though the set has been perfect. Tuna, for instance,

if surrounded in water where the thermocline lies more than fifty fathoms down, frequently sound to below the reach of the net before it can be closed. If the thermocline is shallower than the net, the invisible discontinuity of temperature seems to act as a kind of reflector, and as a result any set that encompasses a school is usually successful. Before the days of the power block, an empty set meant the loss of many hours while the net was being restacked for a new try; now, it can be ready once more in an hour or less.

Handling the mile-long mesh fence now requires fewer hands and is a less formidable task, especially in heavy seas. Simple though the idea behind it, the power block has already made several fisheries more productive to a most revolutionary degree. Patents for several such devices have been granted or are pending in all the principal fishing nations.

Trawls have been used to catch the fish of the ocean bottom at least since the fourteenth century, when Dutch and British sailors, to bring in the flounder of the Zuider Zee and the Thames estuary, dragged wide-mouthed bags of netting, kept open with a pole or beam. The size of their nets was limited, however, and so was their range of operation. With the advent of steam and diesel power, and the use of ice to keep the catch fresh, the trawl came into its own. Before its size could be increased the beam had to be replaced with a less cumbersome device. In present-day trawls the mouth of the net is kept open by means of kite-like vanes or spreaders, known as "otter boards,"* of varying shapes and sizes.

From a modern trawler, lines are shackled to the vanes, one on either side of the net, and still other ropes are connected to

* The origin of the name "otter board" is uncertain; it may be a corruption of "outer"—from the two doors that form the outer part of the net—or it may refer to the aquatic otter. Poachers in England are reputed to have used similar small underwater devices, accurately directed by a string from upstream, to catch the otters that were competing with them for salmon in the streams of certain game preserves.

the trawl's sides or wings. As the trawl is pulled, the resistance of the water against the vanes keeps the net open. Ideally, the obliquely set, upright boards ride gently over the bottom. The best trawling grounds consist of sand, mud, silt, or small pebbles, with no such obstructions as rocks or reefs. The rope at the base of the bag, which grazes the sea floor and is thus known as the ground rope, is provided with rollers or other devices that cause it to slide over small obstacles and at the same time to scare the fish off the bottom and into the net. The head line, which is equipped with floats or a separate opening vane, is often rigged ahead of the ground rope to prevent the fish from passing above the trawl, while the wings deflect them at the sides, directing them toward the opening. Eventually the fish are gathered into the cod end, a bag with a purse string that terminates the net.

The question as to whether a well-rigged trawl actually operated in this way and also, especially, whether meshes of the cod end were narrowed by the weight of the catch so as to prevent the escape of undersized fish was long a subject of debate. Many learned articles have been written on the same questions by members of the Council for the Exploration of the Sea, one of the oldest of international organizations. Eventually, observations made by scuba divers and recorded by underwater television cameras attached to various parts of a trawl showed that it was indeed effective—sometimes too much so, since the escape of young fish was sometimes prevented, particularly at the end of a haul when the end was lined with large old flatfish. The television cameras also showed some fish swimming along with the trawl, between the wings or in the mouth, for a long time before falling back into the bag. Although it appeared that they might well be able to escape, few of them did so, apparently because fish, especially bottom-dwelling species, do not usually dart forward and upward for more than short distances, and thus rarely rise high enough above the bottom to elude the reach of the trawl.

As late as the end of World War II trawls were still being "shot"—to use the fisherman's term for letting down a net—over the side of the vessel. While a trawl is in operation, the ropes lead out over the stern or from close to it. The net cannot be recovered from that direction, however, because of the risk of fouling with the propeller. Thus the boom is used to lift the cod end so as to discharge its contents upon the deck or into the hold amidships. The newer trawlers have been built so as to permit the net to be both shot and recovered over the stern, an idea probably derived from the design of whaling factory ships, which have long had stern ramps or slipways over which dead whales, weighing up to a hundred tons each, could be hauled aboard to be cut up. Now even small trawlers are built with stern ramps that make the handling of big nets easier. The ship's screws are recessed so that the net does not foul. Moreover, the working space for the crew is often enclosed, so that fishing can proceed in much rougher weather than is possible with conventional sidetrawling. Another advantage is, of course, that fewer men are needed to tend the net (Fig. 30).

The present trend is toward building larger and larger trawlers; in the Russian fleet stern trawlers of the Mayakovsky class have a displacement of over three thousand tons. These vessels are almost like factory ships. Often they take on the catch of a smaller vessel to be frozen or made into fish meal. The Russians and Japanese have had increasing success with ships used solely for such purposes; like those used in whaling, these floating factories employ a number of smaller catcher boats, which trawl rather than carry harpoons as the whale catchers do. The transfer of cargo at sea is often hazardous, since almost always there is a swell, even when there are no waves, and the two vessels have to be close yet protected from scraping against each other. Moreover, their decks are not usually of the same height. The same problem still attends the apparently simple task of transferring passengers from one vessel to another.

U.S. Bureau of Commercial Fisheries

Fig. 30. Russian stern trawler operating in the western North Atlantic. Note otter boards on stern.

One solution to the problem of transfer, which has been developed on German trawlers and factory ships, has been to make trawls with detachable zip-on cod ends or purses. When a filled trawl is hauled to the surface, the crew of the catcher-trawler detaches the cod end, which is usually buoyed up by the inflated swim bladders of the fish in it (Fig. 31), and then proceeds to hitch it to two inflatable rubber floats connected by a line and provided with a radar reflector, a rotating radio transmitter, and lights. When this operation is complete, the crew attaches a new cod end to the trawl and proceeds with the fishing. Meanwhile, the crew aboard the factory ship tracks down the floating assembly, grapples for the line that connects the two floats, and hauls the filled bag of fish aboard over the stern ramp. Emptied trawl bags are affixed to the buoys and may be set afloat several at a time, for the catchers to pick them up at prearranged positions. Catches stored in this way

R. Brigham, U.S. Bureau of Commercial Fisheries

Fig. 31. A full trawl. The swim bladders of all the fish expanded when the net was raised so that the full net now floats; the idea of having detachable cod ends may have been sparked by observing this.

are still found to be in good condition after drifting for six hours, and clearly the method saves much time between hauls.

The larger a factory ship the more catchers are needed, and it may well be that there is an economic limit to the operation. Some fisheries economists believe that the limitations imposed by the maximum prevalence of fish in any oceanic area, and by the cost of building and running the boats, may lie between 10,000 and 14,000 tons even for a prolific fishing ground, and already certain fish factory ships of this size have been built by

the Japanese. In this age of specialization the trend has been toward spending much of the time fishing and relatively little of it in processing the catch, at least on the fishing vessel itself. Hence the building of factory ships and large freezer-trawlers with a huge storage capacity. Both Russians and Japanese have aimed at the same result, but have gone about it in different ways.

The Russians have built large fleets of fishing vessels that stay at sea for months, including factory ships that prepare everything from fillets to fish meal, or from canned sardines to cod-liver oil, and 3,000-ton stern trawlers that mainly freeze their catches. Transport ships, veritable floating warehouses, provision the fleet and return the frozen catch to home ports. The high seas, beyond the limits or the coastal jurisdiction of nations along their shores, are international territory, and the creatures inhabiting those waters belong to everyone and to no one. In legal and economic terms they are international common property. Thus a fishing fleet that is relatively independent of shore bases will be less liable to the hazard of international entanglements.

Recently, however, the Soviet Union has been able to secure a fishing base in Cuba that will service a hundred or more trawlers, and one or two more such bases in Egypt are now envisaged. In this practice the Russians are following the practice of the Japanese, who handle the provisioning and servicing, as well as the processing of the catch, of their numerous fishing vessels largely from a worldwide system of bases. Japanese joint companies for fishing and processing are registered in some thirty-five countries. Consequently, Japan has fewer factory ships and freezer-trawlers than the Soviet Union—though she still has many more than any European nation, not to mention the United States.

Imaginative fisheries experts, seeing yet another way of increasing a vessel's fishing potential, suggested at the Inter-

national Fishing Gear Congress held at Hamburg in 1957 that future trawls might be attached to self-propelled otter boards or trawl doors. In this age of automation and the remote control of satellites, the idea is by no means farfetched. In fact, telemetered dirigible torpedoes are already in existence, and so are underwater jeeps operated by remote control. A factory boat might control several of these trawls for fishing at staggered periods, to be recalled when space was available to process the catch. The trawls would be equipped with instruments that would convey to the skipper whether or not they had been working properly, along with the amount of the catch. If such gear becomes economical—and I have little doubt that it will—the number of these catchers attached to a factory ship can be greatly increased over those that are tied to the boats themselves.

Purse seines fish at the surface and trawls fish along the bottom. What, then, of the fish that live close to but not directly on the bottom or those in mid-water, at depths of two or three hundred meters? The idea of trawling in mid-water for shoals of fish is as old as trawling the bottom, but it could not be carried out until after World War II, when fish-locating devices were perfected. Fish in mid-water can be caught only when they have been accurately located and only if the net can be manipulated so as to meet them head on. In the detection of bottom fish by means of sound or ultrasound, the nub of the problem is to distinguish the echo produced by fish from that of the bottom itself. The wider the beam the more suitable it is for assessing the nature of the ocean bed but the more unsuitable for detecting fish, and vice versa. Fish that are not directly below the sound transducer cannot be distinguished from the ocean bed, and definition decreases with increasing depth. Thus fish a foot or two from the bottom can be made out in water that is 60 feet deep, whereas in 600 feet of water the echo sounder will record only fish that swim 12 or 15 feet

above the bottom. Various ingenious methods have been devised, for example, the use of oscilloscopes, which permit enlargement of the bottom section of the echo—an obvious advantage, but one that is offset by the need to watch the screen continuously as compared to the automatic tracing by a conventional echo sounder. By electronic means the bottom echo can also be somewhat suppressed and the distinctive echo of the fish enhanced. Even so, shoals of fish at mid-depth show up much more distinctly than those near the bottom.

Mid-water trawling, which originally required two ships but is now possible for one, must bring fish and trawl together in order to be successful. Spreaders have been redesigned to respond in a reliable and accurate fashion to the raising of the trawl when the towing speed is increased and the lowering of it to the presumed level of the fish shoal when the boat's speed is reduced. In order to have the trawl intercept the fish, accurate records of its depth and path had to be taken. These were secured by placing depth sensors on the otter boards and connecting them to a recorder in the wheelhouse, next to the echo sounder. An error in depth assessment of only a small percentage, however, would cause the operation to miss the shoals completely.

Mid-water trawling is not yet widespread. Only advanced fishing nations have experimented with the needed gear. Yet echo soundings taken in many parts of the northern and temperate seas indicate that there are large schools of cod, hake, or haddock far enough above the bottom to evade the reach of conventional trawling, and that many millions of pounds of currently unharvested fish could be gathered with mid-water trawls. Recently, for example, an experimental mid-water haul off the coast of Washington by the U.S. Bureau of Commercial Fisheries, using a trawl whose depth could be correlated exactly with that of the fish schools at 300 feet visible on the echo sounder, gathered 42,000 pounds of Pacific hake in one hour (Fig. 32).

Richard L. McNeely, U.S. Bureau of Commercial Fisheries

Fig. 32. A 42,000-lb. catch of Pacific hake taken with a pelagic mid-water trawl in a one-hour drag.

Spectacular as the experimental catches made by this method may be, even mid-water trawling still employs what is no more than a modification of age-old fish-hunting techniques. Hunting on land underwent a revolution with the invention of gunpowder. Except for the whaling harpoon—which is propelled by explosives, makes its trajectory in air, and meets its target at the water's surface—gunpowder and its modern derivatives cannot be applied to hunting in the water. But attracting fish by means of an electrical field and subsequently stunning them electrically would appear positively magical to a primitive fisherman who might find nothing mysterious in modern trawling.

The principle of electrofishing is the same technique that permits an electric eel to stun its prey, namely, the emission of brief, quickly rising, and slowly decaying current pulses, fractions of a second long. In an electric field set up by such pulses, fish will swim toward the anode, become stunned, and then float for a time. If the current is not too strong and if it is

turned off after having produced these effects, the fish may recover. Most fish-conservation agencies now use such tools for sampling trout streams, since evidently no harm is done to the fish by the experience. But there is a difference in conductivity between fresh water and salt; the latter, because of its high ion content, dissipates electricity like a sock full of holes, so that electrofishing in streams and lakes requires but a small fraction of the electrical energy that is necessary to produce the same effects in the sea. Also, unfortunately, the reach of an electric sea-fishing device declines rapidly with distance, and it is unlikely that considerations of human safety and power requirements will ever permit its development as a tool that can gather fish from far away.

Nevertheless, electricity does have some spectacular applications to ocean fishing. Once a school of herring or sardines has been surrounded by a conventional purse seine and the bag has been closed, a pump near the vessel designed to convey them to the hold could be electrified. The fish are attracted toward it in such a way as to be sucked up more safely and with a smaller pumping force. An added advantage is that the fish struggle less and are of better keeping quality than those secured by conventional methods. In another electrical innovation, a school of fish is sighted, the vessel steams closer, and then a floating harpoon with an electric head is shot into the school. As the fish gather around the harpoon, it is retrieved, and near the ship it is replaced with an electrified suction hose. The larger the fish the less the power required and consequently the greater the range of the device. Its present range, based on the amount of power that can be produced economically from fishing boats, is limited to about a hundred feet but no doubt this can be extended.

Fish that have been located near the bottom, at a depth just beyond the reach of a purse seine, might be lifted by means of an "electric fish magnet" that is monitored with an echo

sounder and lowered above them. Electrotaxis—that is, the attraction to the anode—lasts a few minutes; then the fish are stunned and sink. The period of the attraction may be long enough to raise the school within reach of a seine which has already been set. As the seine is pursed and the now stunned fish begin to sink, they fall onto the netting instead of dropping to the bottom.

Trawling might also be made more effective with the help of a pulsating electric current. Fish could be attracted into the trawl, the doors of which would act as an electric magnet. The cod end would be fitted with an electrocuting mechanism, to be combined with the attractor without increasing the power, so as to bring in fish that hardly would have struggled and would thus be of superior keeping and eating quality. A similar device was recently tried to raise shrimp, which burrow just below the surface of the silt during the day, in an attempt to free shrimp fishermen from the time limits which the natural habits of the animals impose on their fishing periods. The experiment succeeded well enough to make it probable that in the future this kind of shrimp may be netted during the day as well as at night.

A favorite evening pastime at many marine biological stations is to extend a strong light from a pier, close to the water's surface. Even for an old hand there is a fascination in observing the creatures that are attracted to the light. At Woods Hole, on Bermuda, and at other marine biological centers I have seen dozens of old and young biologists lying face down, heads projecting beyond the planks while they gaze at the blue-black water a few feet beneath them. The first creatures to gather are the plankton, appearing as white dots in the beam of the lantern; then squids and arrowworms may appear, and soon there will be fish, which are apparently so disoriented by the light that they may even bump into the posts of the pier and are easily scooped up with a dip net.

No wonder that fishermen take advantage of this reaction of fish to light in order to attract and subsequently to capture them. What produces the reaction is not clearly understood. In certain species it would seem to be related to a preference for low light intensities—since they are known to keep to the depths during the day and to rise at night—added to the disorientation and attraction that follow upon being exposed to a strong light after their eyes have become adapted to darkness. In other species, notably the kilka, a small herring native to the Caspian Sea, the attraction is believed to be a feeding reflex. Whatever the cause of the reaction, it is widespread enough that lightfishing is successful in many parts of the world.

In the Caspian Sea kilka are caught by the ton when hoses equipped with special lights at the intake are lowered to the level frequented by the fish at night. The depth varies with the season: the kilka go deepest in winter, congregating at between 100 and 200 feet, possibly because the water nearer the surface is too cold for their comfort, possibly because the animals that are their source of food congregate at those depths. Several hundred Russian vessels regularly engage in kilka-fishing with lights, and the attention of many Soviet researchers is devoted both to the technology of this peculiar fishery and to the reactions of the fish to light.

In the Mediterranean many fishing boats carry scaffolds in the bow, to which strong lights are attached. These are used in night fishing for squid as well as fish—a practice depicted by Picasso in *Night Fishing at Antibes.* More satisfactory to the fisherman—since, theoretically, he can have a good night's sleep while attracting and gathering his fish—is an arrangement of set nets and lamps used by the Japanese, whose coastal fisheries still supply an important share of the people's protein diet. This is especially true in the less industrialized parts of the islands, where many traps equipped with leaders to deflect

the fish into the nets are set in bays and near promontories. A few of these traps had series of submerged lamps leading into the sea—some to a distance of 1,250 feet—and the wings of the net. One experiment made use of twenty subsurface lamps spaced at approximately equal intervals, the next to the last one at the entrance to the net and the last inside the net itself. All the lamps were turned on at dusk; then, when fish were seen to have gathered, the farthest lamp was switched off, to be followed a few minutes later by the next, and so on until the fish had been led, step by step, through the entrance of the net. With the lamp in the net continuing to shine throughout the night, the operation might be repeated several times. The net was emptied in the morning, just before dawn. The catch was easily twice that of a net without lights. With a set of programmed switches, fishing by this method might indeed become quite independent of human attendance and automated fishing might be said to have arrived. What the fisherman would do with his free time remains to be seen. One doubts that he would go fishing.

Methods of Preservation

Catching fish, by whatever method, is but the first step in a time-honored process. The next is to preserve the catch so that it will be fit for human consumption. Freezers and tin cans are indeed a boon in preserving perishable foods. Though we tend to take them for granted, they are both only decades old, at any rate on such a scale as they are now employed. In more primitive times very different techniques were used in handling fish, a very perishable source of protein. The following recipe, from a classic cookbook of ancient Rome, is an example:

> It is best to take large or small sprats, or, failing them, take anchovies or horse mackerel, or mackerel, make a mixture of all and put this in a baking trough. Take two pints of salt to the pack

of fish and mix well to have the fish impregnated with the salt. Leave it for one night, then put it in an earthenware vessel which you place open in the sun for two to three months, stirring with a stick at intervals, then take it, cover it with a lid and store it away. Some people add old wine, two pints to the pint of fish.

This produced a fish sauce known as *garum.* Further instructions on how to make it and what to do with it are to be found in *The Art of Cooking* of Apicius.

Such fish sauces and fish pastes, most of them fermented, figured prominently in Roman cookery, and preserved fish of all sorts was important in the diet of ancient times. Although the Roman emperors and their households could afford to send chariot relays to the Alps to keep their cold-storage dugouts, or *frigidaria,* supplied with ice, the common people had to be content with *salsamentum,* or fish sausages, and with salted and pickled or sun-dried fish.

Some ancient seaside towns such as Antipolis, the modern Antibes, were famous as exporters of garum and other fish products. A traveler walking through such a port after the fishing boats had come in would have encountered much the same sights and smells as may be encountered today in many parts of the Far East. There a chain of workers may be seen passing baskets filled with fish up to a foreman, who spreads the fish in large wooden vats that stand in open sheds thatched overhead with bamboo. With a wooden rake the head coolie spreads a layer of fish, followed by a layer of salt in about equal proportions, the layers at the top of the vat receiving progressively more salt than those at the bottom. After a few days the liquid is drawn off and poured back from above. The same process is repeated several times; then a wooden or bamboo wickerwork cover is placed above the vat and weighted with rocks to hold it in place.

The concoction is ready after fermenting for anywhere from six to eighteen months, depending on the size of the fish. Then the vat is tapped and a clear golden liquid is drawn off, usually

into the earthenware crocks that are used for shipment, just as they were for the *garum* of ancient Rome. The sauce is called by many regional names—*tuk trey*, or "fish water," in Cambodia, and *nam pla* in Thailand, for instance—but it is best known by the Vietnamese appellation *nuoc mam*. It is very salty and has a sharp, cheeselike, somewhat fishy, but not unpleasant odor and flavor. I became very fond of it during a stay in Cambodia, and I still prize some bottles of a vintage product made of shrimp, which comes from a certain small area on the Gulf of Siam, and which I use to flavor soups, fish, and even steak.

Besides being a tasty (though highly salted) condiment that gives flavor to the often monotonous rice diet of Southeast Asia, *nuoc mam* is rich in amino acids—so rich, in fact, that fortified with a few vitamins it has been used in place of milk to feed orphaned babies in Cambodian hospitals. Ten million gallons of *nuoc mam* a year are said to have been consumed in what was once French Indochina. For many of the poor of the region a few spoonfuls of it a day are the main protein intake, supplemented only by an occasional helping of fish paste.

Such pastes are usually made from the small fish that pullulate seasonally in the warm tropical waters. Like the Mediterranean towns in ancient times that made similar products, each country has its own special recipes. Usually the fish are cleaned first, sometimes by treading them like grapes, submerged in baskets, to remove scales and remains of entrails, and then salted. Rice, pineapples, papayas, ginger, bananas, and other such ingredients may be added before the mixture is placed in a closed container for incubation. After several months the vats may be opened, though more time is required before the better varieties of fish paste—or what I prefer to call fish cheese—are ready to eat.

That most Westerners find fermented fish repulsive is clearly no more than a culturally induced prejudice, since the same people often relish other mildly fermented products.

Cheese made from cows' or goats' milk relies on bacterial action no less than does fish "cheese," has similar nutritive advantages, and like it can be stored more easily than the parent substance. The two even smell very much alike. In Phnom Penh I once watched a Frenchman turn green upon having a dish of fish paste placed before him at a banquet—yet a little later he was trying to arrange with an Air France pilot to have a well-ripened Camembert brought in on the next flight from Paris.

In the East, where fish are the staff of life, ways of preserving the perishable catch beyond the fishing seasons are all-important. In the West, where fish are no less perishable, ingenious methods have been developed, some of which have actually changed the fate of nations. In the Hanseatic League, a trade association that constituted the first international fisheries trust, with Lübeck as one of its leaders, some of the member towns showed a herring in their coats of arms. The League, which was made up principally of free German towns, was at the peak of its power during the fourteenth and fifteenth centuries, which saw a great abundance of Baltic herring. The cities of the League sold salted, pickled, and smoked herring in Russia and Poland, in Flanders, France and Spain, and in Britain. They also shipped beer, as befitted good German merchants, and they had a hand as well in the Norwegian fur trade and in Swedish minerals. Moreover, since salt was necessary to preserve the fish, they ran salt refineries and carried on a trade in salt. The quality of Hansa herring was strictly controlled. In order that small or inferior fish would not be placed in the middle of the barrel, the packing was closely supervised. In the late fifteenth century, with the decline of Baltic herring, probably as a result of hydrographic changes, and the rising power of Denmark, the Hanseatic League lost its importance; but the last of its guildhalls did not close until the middle of the nineteenth century.

As the herring fishery shifted to the North Sea, a new chapter was written in the history that linked methods of fish preservation with the fate of nations. This time the Dutch played the leading role. At some time around 1400 one William Beukels is said to have perfected an improved method for the treatment of herring. Fish cured by this method were gutted in a special way so as to retain some of their internal organs, thus providing enzymes that, together with the brine, produced a softer, better-tasting, and longer-keeping salt herring than anything the Europeans had tasted before.

Salt herring was very important during the Middle Ages. Not only were armies and navies provisioned with it but also the tables of nobles and kings, and those not only during Lent. Along with other fish, variously preserved, salt herring accounted for a large part of the proteins in the diet of clergy and common people. The Hundred Years' War saw a "Battle of the Herrings," involving the safe delivery of 500 cartloads to relieve the army of the Duke of Suffolk, which had laid siege to Orléans. It would appear from accounts of the skirmish that herring barrels were used in those days as barricades, quite aside from the part played by their contents in maintaining the army's fighting strength.

No wonder, then, that Beukels, the reputed inventor of the "Dutch Cure," ranks as a sort of national hero, despite uncertainty about the dates of his birth and death. Probably he did not invent the method, which would seem already to have been brought to Flanders by the Hansa merchants, but rather had a hand in organizing the manufacture of pickled herring with strict regard to control over its quality. Not only processing but also the fishing itself—from sites mainly off the eastern shores of England and Scotland, during a season lasting from around the first of July to December—was carefully regulated. The amount and type of salt was standardized; so was the kind of barrel to be used. The fish were cured and packed at sea in

special vessels, the "herring buses," which carried coopers, whose task it was to make the barrels tight, along with the fishermen, some of whom were skilled picklers. Special tenders rushed early catches to Holland for branding and immediate distribution to the market. Toward 1700 a third of the Dutch population is said to have been engaged in trades ancillary to the fishery. Perhaps because of superior organization, as well as a product superior to that of the Hansa, the Dutch remained eminent in North Sea fisheries for nearly three hundred years.

"Those of Holland and Zealand carry on a very plentiful and gainful trade of fishing in the sea here for herrings . . . the English out of a lazy temper resigning the gain to others," wrote William Camden in his *Britannia.** He was indulging in hyperbole; in fact, Britain long had a flourishing fishing industry of her own and British statesmen from Elizabethan times onward frequently developed schemes for entering into active competition with the Dutch for the lucrative trade in salt herring. Eventually, with Britain's development as a sea power, their efforts succeeded, and by the opening of the nineteenth century British salt herring was a sought-after commodity.

The earlier British fishery had been in part also after herring. Scottish ports were noted for a strong-smelling, salty smoked fish, the proverbial "red herring." Other kinds of fish, variously treated to withstand the attack of the ever-present bacteria and to allow transport and storage, included dried codfish, salted or unsalted, and such related products as the Poor-John, a dried salt hake, to the odor of which Trinculo, the jester, compares Caliban's strong scent, in *The Tempest,* Act II, Scene ii.

Except for making a virtue of necessity, enlisting the services of bacteria, and developing a taste for fermented fish—as the Romans once did and the Asians still do—before the advent of freezing and the canning process there were few ways of keeping fish. It could either be salted so strongly that no objectionable bacterium would invade the brine, as in pickled

* London, 1586, R. Newberry.

herring, or so thoroughly dehydrated that what little water was left could not be used by the bacteria, as in dried cod or stockfish. Salting can also be combined with other preservation techniques, for example, drying or smoking, as in kippers and red herring.

Herring are fatty fish; they are ubiquitous and so plentiful that more than a quarter of the world's total fish catch is made up of clupeids, the family to which the herring and their relatives belong. They do not lend themselves to any kind of drying because the fat turns rancid before the process has begun. Thus clupeids are generally pickled, smoked, or, in a relatively recent development, rendered into meal and oil. The codfish family, which includes haddock, hake, whiting, and other bottom fish such as flounder and halibut, unlike the herring, are generally lean fish with little oil in the flesh. They do not turn rancid and therefore can be preserved as that durable staple food, dried fish.

Of such species cod is clearly the most important. During the seventeenth and eighteenth centuries there was rivalry between English and French fishermen over the best drying beaches in the rich New World fishing grounds—a rivalry that contributed to the War of the Spanish Succession and the Seven Years' War. The abundance of cod in New England coastal waters gave the Commonwealth of Massachusetts a strong start in life, and in the House of Representatives at Boston there hangs a cod "as a memorial to the importance of the cod fishery to the welfare of this commonwealth." In fact, controversies over whether the colony or the mother country was to supply salt cod for the slaves in the West Indies, and thus to develop a lucrative cargo trade, was not the least cause of friction between old and new England.*

* Salt cod is still an important source of protein in the West Indies. Cuba has recently acquired one in a series of large trawlers, with which she will join the several nations now engaged in the cod fishery of the western North Atlantic.

Most food stores in the West Indies still have little resemblance to any supermarket. They are found in small houses, built with thick walls for the sake of coolness, with blinds closed against the midday heat and the flies. It is dark and cool inside and the air is pervaded by the unmistakable, musty odor of salt-encrusted, bone-hard sides of cod, hung from the rafters or laid on shelves. Island hopping in the Caribbean makes a visitor aware of how the cultural stamp given by the colonizers varies from place to place, but though the styles of houses and the width of the streets may differ, the smell of salt cod is common to them all.

Most food tastes are acquired, and the taste for cod is no exception. It goes back to the heyday of the sugar plantations, when neither master nor slave was much inclined to go out and fish in the nearby waters. A nutritive protein that came in slabs from which pieces could be broken off to produce a savory dish, after having been soaked overnight in water, was clearly a boon. Some bacterial action occurs in cod before the water content is reduced by the drying process and is responsible for the flavor that contributes to the popularity of dried cod in the often-monotonous fare of tropical peoples.

The simplest cod-drying process consists of gutting and splitting the fish before drying it in the air. Much bacterial decomposition goes into the process, lending the product, stockfish, a peculiar flavor that is now relished by many Africans. Norway and Iceland are the chief suppliers of the "Afrikafisk"; a modern freighter load may feed 35,000 Nigerians for as much as a year. Apart from the flavor, in the humid tropics, stockfish has another advantage over dried salt fish: whereas the latter is covered with a glistening layer of salt crystals that absorb water from the air, stockfish has no salt on the outside and does not take up water.

The near monopoly by the nations of Northwestern Europe upon the world trade in dried fish is due in part to historic and

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Fig. 33. Tons of cod; a trawl catch aboard a New England trawler.

in part to zoogeographic conditions. The codfish family occurs in the cool waters along the continental shelf of the Northern Hemisphere, where the shelf area is twice as extensive as that of any other ocean. During the Middle Ages, with the rise in historic importance of regions north of the Alps, adventurous

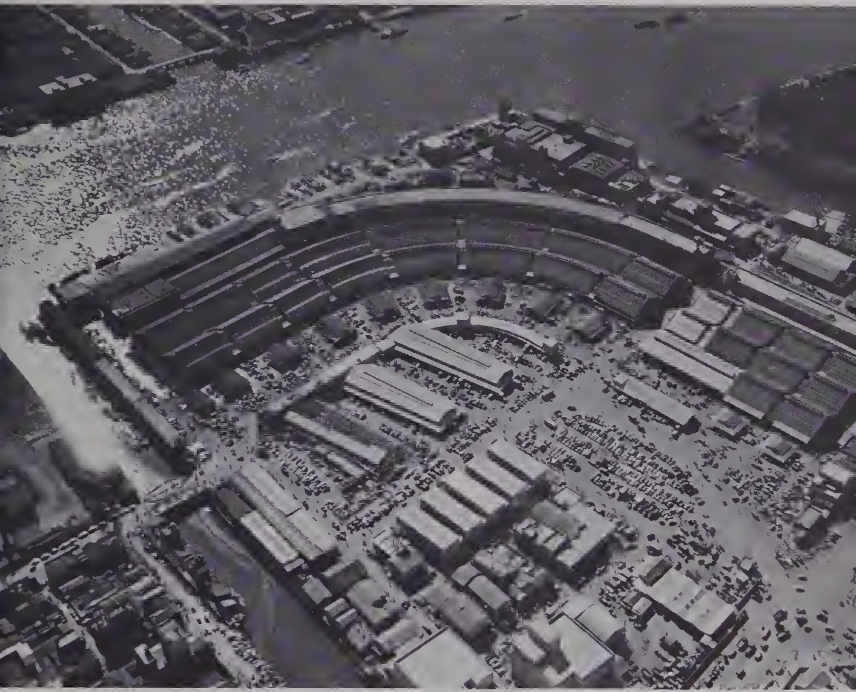
fishermen turned north and west, first fishing off Iceland and later, in the time of Cabot, reaching Newfoundland, where the sea swarmed with fish. Still later they reached the fertile shore waters of the new continent itself—a region where the peoples of Europe, with the recent addition of the Russians as a major fishing power, still fish for cod (Fig. 33) and its relatives.

The Fish Market

Fresh fish " . . . have clear bulging eyes. Their gills should be reddish and fresh smelling, their flesh firm and spring back when pressed and above all, they should have no unpleasant odor," writes James Beard on the first page of his *Fish Cookery.* Unless one is to catch the fish oneself, it is fairly difficult today to buy such a fish, even in the cities near the ocean. One would have to go early in the morning to a big fish market such as the one at Billingsgate in London, the one on Fulton Street in New York, or the biggest of them all, the metropolitan fish market in Tokyo.

That Tokyo should have the largest fish market is not surprising since it is the world's largest city by certain measures, and since the Japanese people must eat much fish to survive (Fig. 34). Every day in Tokyo, between 3.5 and 4 million pounds of fresh fish and shellfish change hands—a daily ration amounting in a year to almost a hundred pounds per capita. By contrast, in the United States the average consumption of fresh and frozen fish is around ten pounds per year. If one includes "secondhand fish," such as those in chicken and hog feed, Americans eat even more fish, some say up to 70 pounds per year. More than 300 different kinds of fish and shellfish, mainly marine species, are involved in what appears to be a complicated sales process.

Even before dawn the boats begin to unload. Large fish such as tuna are displayed close to the boats, acres of them lying



Japan Fisheries Agency

Fig. 34. Aerial view of Tokyo's metropolitan fish market.

side by side. To save space, their tail fins have already been removed, and the tails are notched so as to allow the buyers to inspect the pink flesh and gauge the freshness of the merchandise. Smaller fish are displayed in baskets, boxes, and bins, while wholesalers swarm about them (Fig. 35). As though bearing in mind Mr. Beard's last injunction, each carries a fair-sized metal hook on a wooden handle, which he now and then brings down sharply on a fish, penetrating the skin and securing a tiny morsel of the flesh so as to pass judgment by sniffing (Fig. 36). If it passes the test, the wholesaler may note the

Japan Fisheries Agency

Fig. 35. Scene inside Tokyo's metropolitan fish market.

Author

Fig. 36. Potential wholesale buyer at the Tokyo metropolitan fish market testing the freshness with hooked flesh probe.

number of the lot, or of the fish, in order to bid for it later at the auction.

As 6 A.M. approaches, groups of wholesale buyers cluster about the official auctioneers as they begin their rapid, hoarse, staccato patter in a language intelligible only to the initiated. The buyers seem almost nonchalant as they make their bids, raising a few fingers in the act of scratching an ear or hiding the gesture behind a notebook so that no one but the auctioneer can see (Fig. 37).

Author

Fig. 37. Fish auction at Tokyo's metropolitan fish market.

Next the fish are brought into a shed just beyond the dock, where the wholesalers offer their wares to shopkeepers, restaurants, and private householders. Some wholesalers' stalls specialize in freshly boiled lobsters, brilliant red and sweet-smelling; others offer octopuses, displayed in shallow metal trays where they make pleasing geometrical patterns; still others sell tender sides of bluefin, whose thinly sliced red flesh will be dipped in vinegar and spiced with soy sauce, and which can vie with the choicest rare beef for delicacy of flavor.

As has already been noted, food tastes tend to be culture-bound, the liking of raw fish being one of them. But for reasons of health there are few objections to be raised against eating most fish raw. It is true that a few fresh-water fish, such as northern pike and lake trout, may harbor a disagreeable tapeworm; but few marine fish are subject to parasites that could be transferred to man. Bacterial spoilage, not parasites, is the greatest problem for traders in fresh fish, whose flesh is more readily attacked by micro-organisms than other kinds of meat.

Although fish in all waters carry bacteria on their skins and gills, and above all in their guts, their flesh is certainly sterile so long as the fish is alive. Immediately after death, however, the natural defenses against bacterial proliferation cease to operate, and the flesh may be invaded. Technologists do not fully agree whether it is best only to gut the fish before it is iced or to gut and thoroughly wash it. Unless the washing is done properly and with care, it may cause the spread of bacteria from the gills into the originally sterile body cavity, thus making matters worse instead of better. And, contrary to what would seem to be common sense, cooling the fish to near-freezing temperature does not slow down the growth of all bacterial species equally; nor do antibiotics kill them all. Even freezing to just below 32 degrees Fahrenheit, rather than to a much colder temperature, leaves some bacteria still growing slowly and others in suspended animation, ready to multiply upon thawing. The wooden bins used to keep fish in the holds of the fishing trawlers and in the markets often teem with bacteria, so that a change-over to the more expensive metal or plastic trays is clearly indicated. Icing alone does no more than retard spoilage, which may readily commence even in the brief passage of the fish through auction and wholesale market.

Nevertheless, large quantities of fish are still sold fresh and consumed the day they are caught, especially in developing

countries. Western housewives, on the other hand, now buy most of their "fresh" fish frozen, thanks to an elaborate preservation technology. Frozen fish, a dish that only fifty years ago would have been restricted to the table of a gourmet close to the seashore, may be produced from Columbus, Ohio, to Nizhni Novgorod—for the Russians take, if anything, better care of their fish than does any Western nation.

After a catch made weeks from the home port, the fish are gutted, chilled in supercooled brine, and deep-frozen, often in the form of fillets. The cutting wastes are rendered into fish meal or into animal feed aboard ship. The secret is, then, to handle the cargo at all stages, down to the retailer, so as not to thaw it until the fish is to be prepared for the table. If it is thawed and then refrozen it will have lost through drip some of the cell contents, and with them the complex aromatic substances that make for the subtle differences in taste between a sole meunière and a broiled snapper.

Long before the days of deep freezing (which really began only after World War II) it was known that plain ice retarded spoilage. But in many parts of the world, ice is hard to come by, and even in the London of the early 1800's fresh fish was considered a luxury. In those days fish had to be placed in live wells that could be towed upriver, a process that raised their price; or they were delivered by carriage, which for the trip between Yarmouth and Billingsgate involved twelve changes and a total of forty-eight horses. Charles Cutting reports in his *Fish Saving* that in 1833 a turbot sold in London for as much as 3*s.* 6*d.* (50 cents at today's rate of exchange). Clearly only the rich could afford such fare at a time when a laborer's daily wage was probably less than a shilling.

In America the use of ice for keeping fish took hold relatively late, even though natural ice was available. In the 1840's vessels out of Gloucester used just enough ice to keep the fish holds at room temperature, since it was believed that contact

with the ice would lead to rapid spoilage. There appear to be two reasons for this belief, one biologically sound and the other not. The holds were so contaminated that any drop of water from the ice carried millions of bacteria, and the fish buyers were disturbed by the pale spots that develop on a fish where it has been in contact with ice. Such paling is a natural reaction of fish skin after death, and the pale spot soon disappears when the ice is removed and fish comes into contact with fresh air.

The token use of ice was superseded, with the result that today vessels that do not deepfreeze their catch carry as much or more ice than they do fish. The trend clearly is toward freezing, and although the sale of cellophane-wrapped fillets does away with the pleasure of choosing by shape and color from a fishmonger's display on a bed of ice, it does at least make for a wider distribution of better food than ever before. And that, after all, is progress.

The persistence and the incredible versatility of bacteria goaded human inventiveness into making fish sauces, curing, canning, and keeping fish by still other methods. One of them that is perhaps no less promising than the making of fish protein concentrates mentioned earlier is the manufacture of fish sausage. Large displays of this Japanese specialty can be seen in the Tokyo fish market. It can be made from almost any kind of fish, but is especially suited to those for which no other market exists at present. The fish is cooked and shredded, mixed with salt, food additives, and starch, then flavored with spices and laced with lard. So far the recipe is not unlike "gefilte fish." But the addition of whale meat, made durable with traces of bacteriostatic agents, before the sausage is stuffed into plastic casing, adds a new gastronomic dimension. There are fish "ham rolls," for instance, containing whale meat in place of ham; there are others resembling such things as frankfurters, and still others that may appeal more to an Eastern than to a Western palate. All are cheap (25 to 40 cents a

pound), and pasteurization makes them relatively durable without refrigeration. Thus fish sausages are popular in the rural areas, where the standard of living is lower than in the cities, and for the same reason they give promise of varying and increasing the protein fare of developing nations.

Fish sausage, or *kamaboko,* to use its Japanese name, has suggested to scientists of the U.S. Bureau of Commercial Fisheries the idea of using the large surplus of buffalo fish in the fallow inundated rice fields of the southern states for making fish sausage. With the help of experienced food processors, the experiment, which remained just that for lack of promotion funds, produced some sausages that give promise of appealing to the most American of tastebuds no less than sausages made from pork or beef.

In the battle against bacteria, atomic technology and the phenomenon of ionizing radiation also have been harnessed. In the quest for a good peaceful use of the atomic reactor, gamma-ray-emitting isotopes of some metals were used to irradiate various foodstuffs, with the intent of killing bacteria and rendering the cellophane-wrapped and sealed food sterile forever after. Fish, because of their proneness to bacterial spoilage, were among the first to be tried. Though the method works with some foods, notably dry products, it does not yet work with fish. The bacteria are killed, but the submicroscopic barrage of radiation brings about subtle changes that affect the taste. Even advocates of this preservation method—which, incidentally, is still very expensive—admit that fish made completely sterile by radiation has a rubbery consistency and tastes "like burnt feathers." Recent tests which seem more promising from the standpoint of taste are based on a compromise: a smaller dose of radiation, perhaps not killing all bacteria, for the sake of retaining some flavor.

Another modern preservation technique, combining freezing and drying, raised hopes but proved equally ineffective. The

idea was to quick-freeze the fish first, arresting all processes of decay and spoilage, and then to bring about rapid sublimation of the ice under greatly reduced pressure. When thus dehydrated and kept well below freezing the fish could be preserved almost indefinitely. All that had to be done to reconstitute it was to place it in a dish of water before cooking. It does indeed keep indefinitely; it takes up water, and it can be made into a dish that is easily digested. Unfortunately the taste suggests a dishrag that has been put through a Waring blender.

Deep freezing has been a boon to the Western housewife. Precooked foods, among which fish dishes figure prominently, have reduced her chores, and at some future date perhaps even irradiated and freeze-dried fish may come into their own. Yet there are still a few people who like to go to the fishmonger's, whenever they can find one, and select just the right plaice or snapper, caught yesterday, resting appetizingly on a bed of ice. Such persons even like to dress the fish themselves and turn it into a work of gastronomic art, and for their sake it is to be hoped that the fresh-fish markets, whether wholesale or retail, will persist.

Keeping the Catch

In 1809 the French chef Nicolas Appert won a prize from his government for a new method of preserving foods which relied on heating under seal. Luxury foods, including lobster, were soon "appertized," as the method was called after the inventor. At first they were put up mainly in glass. The use of tin cans on a large scale for preserving fish awaited both the perfecting of the machines that make the cans and the advances in bacteriology which made canning a reliable method of food preservation by the turn of the century, an occasional case of botulism poisoning notwithstanding.

Canned fish are generally the fatty kind; they include salmon, sardines, herring, and now tuna. The relative impor-

tance of the canning of fish—and other foods—decreases as the standard of living rises, and with it the prevalence of refrigerators and frozen foods. Russia and its satellite countries still preserve much of their catch in cans, as well as importing canned fish from abroad. Near the equator canned fish is a most important item in the diet of those who can afford something more than fish sauce, fish paste, or dried fish; the consumption of canned fish between the Tropics of Cancer and Capricorn will undoubtedly expand. I remember with relish a meal of Norwegian sardines aboard an Indonesian fishery research vessel, without being troubled by any thought that such fare was perhaps incongruous.

After a car and a television set, a refrigerator is perhaps the most coveted of worldly possessions among those who are on the way to reaching a Western standard of living. It does, in fact, make possible a variety and quality of fare that were unimaginable before 1929. That was the year Clarence Birdseye perfected the plate freezer, in which the food to be preserved is placed between two supercooled metal plates, whose distance apart is adjusted to the dimensions of the product.

Fish frozen in bulk was available before 1930 for wholesale storage purposes, and as a perishable commodity it was one of the first protein foods in home freezer-sized packages. Expensive kinds such as shellfish were mainly packed at the beginning; then, as the process became cheaper, the more common fish were frozen in the same way. The fish that freeze best are, not surprisingly, those that contain little oil, that do not can well but are suitable for drying, such as the cod and other so-called white fish.

At first frozen fish was mediocre fare at best, but with faster, bigger, longer-traveling ships and with improved equipment that froze the catch as soon as it was brought aboard—preferably not to be unfrozen until the fish was ready to be cooked—frozen fish became almost as good as those that went directly out of the water into the pot or pan. Some are decidedly better

than most of the so-called fresh fish available in large city markets, even near the seashore. The quality of frozen food depends, of course, on the existence of an unbroken refrigeration "chain." For fish, this means continual refrigeration from the trawler to the port, and from the port to the inland point of consumption. Adequate refrigeration chains prevail only in America, Europe, Soviet Russia, and parts of Japan.

Frozen fish is still a luxury in those parts of the world where electric outlets are found only in the houses of the rich, and where housewives go to the market daily. In many such places fish supply most of the available proteins. To keep it from spoiling, drying and freezing are alike in that each makes water unavailable to unwelcome bacteria. Both processes require a considerable amount of energy; but whereas the energy required to evaporate the water and dry the fish is supplied free, by the sun, that needed to freeze it must be supplied by man and consequently it must be paid for. To freeze a pound of fish fillets takes, in fact, about five times the content in calories that they supply on being eaten. Furthermore, it is more expensive to transport frozen fish than dried, not only because of such required paraphernalia as refrigerated trucks and railroad cars but also because the dried fish have a content of only 15 to 20 percent water, as against the 70 or 75 percent for frozen fish. Thus dried fish remains a staple for many; indeed, dried cod or stockfish is still often cheaper in tropical lands than the local fresh fish. But since one of the landmarks of technological advance consists of cheaper and more abundant sources of energy, the practice of freezing fish is certain to increase.

Meal and Protein

It was the practice of some Algonquin Indian tribes to place a gizzard shad or menhaden (both small fishes that occurred by the millions off the east coast of North America) in each mound

of corn they planted. This was a very roundabout and inefficient method of incorporating some of the valuable ingredients of an abundant fish into human food. Marco Polo told of a better way, namely, the feeding of dried fish to cows, sheep, camels, and horses in China. Even in the United States, at Provincetown, in the nineteenth century there were fish-eating cows which freely partook of the offal from fish cleaned by the seashore.

Whatever fish is eaten by cows on Cape Cod today comes to them in the form of fish meal, and in fact cattle now consume less fish meal than pigs or poultry. More than 20 percent of the world's entire catch of fish is rendered into meal and its valuable by-products. At present the largest tonnage taken by United States fisheries—over 2 billion pounds annually—consists of menhaden, not one ounce of which goes directly into the pan or cooking pot. Peru's total catch, which lately exceeded even that of the U.S.S.R. and Japan, is turned into fish meal, and as we have noted, the floating factories of Japan and Russia, aside from taking vast amounts of fish for human food, convert into this dehydrated high-protein feed additive a quantity of fish that exceeds the entire U.S. catch.

Fish meal is mostly made from small, often bony, fatty fish such as herrings, sardines, anchovies, and menhaden. The final product consists of small grayish-green flakes that smell, not unpleasantly, of their source, with sometimes just a rancid whiff from the residue of fats contained in it. Fish meal is eaten mixed with a base consisting of plant material such as alfalfa meal or bran, and its value as feed is in its being from 60 to 70 percent animal protein, with all the essential amino acids, in containing vitamins, especially those of the B type, and in being richer in phosphorus and calcium than the plant feed base.

The fish destined to become meal are usually cooked to begin with; then the cooked mash is pressed into a sort of cake

to eliminate some of the water, the oil is squeezed out or separated from the mash by means of special fat solvents, and the mash is then dried, shredded, and bagged. A low fat content is important if the meal is not to go rancid in storage, and also because the diet of most animals should not be high in fat. Various refinements and special techniques are used to obtain a low-fat, low-moisture, high-protein product. One of these is to concentrate the liquor from the first pressing, which contains about a fifth of the original nitrogenous solubles from the whole fish, and to add it to the meal after the oil residue in the liquor has in turn been removed. The press, or stickwater—which is sticky because of the fish extracts it contains—is marketed separately and is used for soaking plant materials to make a more nutritious feed for hogs.

Fish oil is also becoming increasingly valuable in its own right. It is made up largely of unsaturated fatty acids, which form a base for the manufacture of margarine and cooking fats. After hydrogenation, which renders the oil solid, it is used for making soap and candles, and as a paint base—a particularly valuable use since paints made from it are heat resistant and form a less brittle surface than those derived from vegetable oils. Fish oil is also used in waterproofing, in making varnishes, in the linoleum industry, and for leather dressing.

The impressiveness of such industrial uses notwithstanding, it is to be stressed that without fish meal the hog-raising industry today would be in such dire straits that it would be obliged to retrench severely, and that without a worldwide supply of fish meal the poultry industry of Europe and America would collapse. Chicken would once again, as it was not so long ago, be a relatively expensive food rather than the cheapest meat a housewife can buy.

If this kind of feed can be produced from fish, cheaply enough to be fed to animals, could it not be made into human food directly—perhaps with some refinement such as further

reduction of fat—at only a slight increase in the cost? It may well be argued that the loss inherent in having to go through one more link than necessary in the food chain would be avoided, making available a cheap, protein-rich food by the billions of pounds. Industrial techniques, and the fact that it weighs little in proportion to its protein content, and that because it is dehydrated it would have a very long spoilage-free storage life, would make it far superior to its predecessors, the fermented fish sauces and pastes of antiquity and present-day Asia.

The Protein Advisory Group of the United Nations (consisting of UNICEF, WHO, and FAO) recently stressed that such a fish protein concentrate would be of great potential value as a food additive. The concentrate would be made of whole fish for the sake of cheapness, and the particular beneficiaries both of the proteins and of the calcium from the bones and phosphorus from the skin and scales would be the millions of hungry children in the world. The world's fishing industry also would benefit. At present the Western fishing nations, and notably the United States, take only selected species for which there is a traditional market, and often use only parts of the fish, such as fillets. The nonfilleted portions are discarded, along with other species that are taken by trawls, because the gear is not selective but scoops up all fish in its path, and there is no process to permit marketing them cheaply. The potential harvest of such species along the coasts of North America alone has been estimated at a net weight of six billion pounds per year. Allowing for the reduction in weight due to the removal of the water that is a main constituent of all living matter, there would still remain a mighty heap of almost pure protein; a teaspoonful of such a powder for each hungry child each day would suffice to normalize his diet.

No wonder, then, that several European nations had begun research into methods of making fish protein concentrates from

whole fish even during World War II. Several processes have been developed, by which whole fresh fish can be turned into a light-colored, tasteless, odorless, flourlike powder, to be admixed in bread, tortillas, or whatever the regional staple may be.

There now exist small plants in Chile and Morocco where people are beginning to eat dishes fortified with FPC (the abbreviation for fish protein concentrates). Sweden, Germany, Switzerland, and of course the U.S.S.R. have done research on the manufacture of this most promising new kind of food from the sea (or fresh water, for that matter, there being no reason why otherwise unusable fresh-water fish or their residue should not be treated in the same way).

Essentially there are two main ways of producing fish protein concentrates. One follows some of the traditional principles of processing fish meal—mechanical maceration, slight heating, and the use of special volatile solvents, later to be removed, as well as the recovery of excess oil. The aim of the process is to be simple, foolproof, and sterile; thus stainless steel is often used. The second process improves upon the traditional bacterial fish digestion methods of the Far East and relies on controlled tissue breakdown by protein-digesting bacteria, molds or yeasts, or by isolated enzymes. Its end product is a paste or broth that can be further dried into a powder with all the ingredients of nutritional value present. This second method is still further from being perfected than the first, though it promises eventually to be more economical and versatile.

The United States, after a series of peculiar events, has now embarked on an official, that is, a federal research program, on fish protein concentrate. Several firms, of which the VioBin Corporation of Monticello, Illinois, had taken the lead, had experimented for many years with methods of making fish protein concentrates from whole fish, using several kinds of

volatile solvent, and had obtained patents for those processes. To be sold for human consumption such products would have needed the approval of the Food and Drug Administration, and in the process of seeking that approval it transpired that the concentrate would be regarded as an "adulterated article," according to section 402 (2) (3) of the federal Food and Drug Cosmetic Act, because it contained portions of the fish (scales, fins, viscera, head, and, worse still, the eyes) not normally regarded as acceptable for human consumption. Lengthy negotiations ensued, after which, in January, 1962, the commissioner of the FDA finally ruled that whole fish could not be used because "consumers in the U.S. would regard the product described . . . as filthy."

The ruling soon came before the meeting of the UN Protein Advisory Group, who deplored this clearly shortsighted decision and stated that the FDA ruling not only prevented sales in the United States but also affected the use of FPC in developing nations. Obviously a Western technical expert would find it difficult to persuade an African or Asian to eat a product that was not considered fit for human consumption in America, or to advise him to install manufacturing machinery, even if it were given to the host country, to make something that was banned from consumption in the land of unlimited opportunity. The same technician would know that the transformation to which the fish are subject in the process is so complete and profound that there is neither fish taste nor fish odor, quite apart from the absence of even the slightest danger of contamination or of carrying diseases. He would also know that an FPC in the country under his care could lead to the greatest nutritional leap forward the region has ever known. But his hands would still be tied.

The commissioner did not rule that the product was indeed filthy but, second-guessing the reaction of the American housewife, only concluded that customers might think it was. Per-

haps college students are particularly enlightened, especially in their acceptance of strange foods. At any rate, several hundred of them at a University of Michigan dance a few years ago relished cookies made with flour to which a good portion of FPC had been added. When they were offered refreshments it was clearly stated that the cookies contained FPC, a protein additive made of whole fish, guts and all. At this information the usual reaction was a pause, a look at the piece of bakery from which a bite had already been taken. Then the students smacked their lips, bit off another piece, and to a man approved and reached for more. One wonders whether the Commission might not have settled its qualms by insisting simply on the mention of whole, uncleaned fish on the product's lable, leaving the promotion to the manufacturer, and there let the matter rest. It seemed incongruous that FPC could not be declared fit for human consumption, it was pointed out by Senator E. L. Bartlett, the chairman of the Subcommittee on Merchant Marine and Fisheries of the U.S. Senate, if the FDA could approve the sale of "grasshoppers which are not filleted and chocolate-covered ants, on which no preliminary [cleaning] work is done."

Reason finally prevailed, thanks to steps taken by Secretary of the Interior Stewart L. Udall and the National Academy of Sciences. A research laboratory of the Bureau of Commercial Fisheries at Beltsville, Maryland, worked out procedures—not unlike those already in use elsewhere—of rendering whole fish into a savory yellowish-white powder, and the FDA pronounced such material, made from hake (Fig. 1), safe for human consumption.

Fish protein concentrate, said Mr. Udall, "establishes a lifeline to a better future for undernourished millions of people throughout the world." It is especially valuable for children, not only to build strong bodies, but more importantly, to develop sound minds. Protein-starved children run the danger

of not being able to develop the necessary myelin sheathing around the nerve cells in their brains. They might never catch up in mental development with other, better-nourished, more fortunate age mates. Even if a child has enough calories, a dearth in essential amino acids will hinder or retard the expression of genetically inherent high IQ's.

No wonder, then, that President Johnson has recommended rapid development of an American FPC industry, on the advice of the Council on Marine Resources and Engineering Development (see last chapter). The hopes of producing, very soon, many tons of FPC a day for export to the hungry around the world may be premature, however. The pilot program authorized by Congress still awaits implementation, though it was pointed out in Senate hearings, in 1966, that $5 million invested in its manufacture and distribution could considerably ease the lot of more than a billion people. It is probably without influence on the course of FPC developments but sobering nonetheless to consider that this cost is equivalent to that of a few hours of the Vietnam war.

There are some other obstacles besides a federal austerity program, such as skepticism on the part of the fishing industry, which considers that one cannot make money on FPC unless one sells it on the domestic as well as the world market. They believe that Americans are not about to take to a flour additive, made from whole fish, the FDA approval notwithstanding.

Yet, FPC will be made and eaten in many countries, first and foremost by the world's hungry but eventually also in America, where it could be added to baby foods and cereals. Perhaps it will even enrich the taste of our already enriched though tasteless bread.

4

New Seed

Harvesting Plankton

The potential use for human nutrition of so-called trash fish in a fish protein concentrate is but one of several ways by which the take of food from the ocean might be augmented. Some of the ways that have been suggested turn out to be pipe dreams when examined with ecological principles in mind. For every such proposal the limits upon the amount of protein that can safely be taken from the sea, without in some way harming the stocks that produce it, must be taken into account. To put the matter another way, the optimum of plant growth within the limitations of the available light and nutrients must be recognized. To be realistic, the proposal must be restricted to forms that can be gathered economically with existing or feasibly projected tools. This is why the utilization of plankton, one of the proposals advocated for dealing with the world food problem, holds no hope even as a partial solution.

That the algae and diatoms that make up the phytoplankton are the primary producers of living material in the sea has already been noted. Their distribution varies not only from place to place but from year to year, and despite certain coastal regions, where the water has the consistency of a thick soup, the sea as a whole is far less fertile than the land. But what of those billions of pounds of protein, carbohydrates, and fats that are contained in the plankton? Why not scoop them

up, rather than leave the task to the fish, since in the process we should also obtain the zooplankton, the microscopic animals that coexist with the phytoplankton on which they feed? Many of the zooplankters are tiny cousins of crab and shrimp and therefore, it would seem, of direct potential value in human nutrition, although some method would have to be found of macerating their hard chitinous covers before they could be turned into plankton flour or a similar product. Phytoplankton is of far less interest as food, both because algae are lacking in certain of the amino acids essential to human nutrition and because the cellulose and silica that make up their cell walls are indigestible.

But even if these objections did not apply, harvesting plankton from the sea on any large scale is and will remain economically impossible, simply because water rich in plankton rarely contains as much as even a tenth of a gram dry weight per cubic meter (just over three thousandths of an ounce per cubic yard). Thus, a million gallons of water would have to be filtered to obtain just one pound dry weight of plankton. Nor is this the only technical obstacle. Fine nets used as filters would soon clog, and if the water was taken in through funnels and piped through a centrifuge, many times the size of the largest present-day fishing vessels would be needed for the operation. Moreover, the larger the funnel the slower the speed of the vessel, and since the filtered water would have to be voided, the harvesting area would soon be diluted, so that the operation would defeat its own purpose. The same objection and the same prohibitive ratio of cost to benefit would apply to land-based pumping of plankton. It has been suggested that plankton might be extracted as a by-product from the many tons of cooling water that are taken in every minute by a modern passenger liner or freighter. Once again, the plant required to filter the necessary amount of water in order to extract the plankton would take up more space than could possibly be

given to a ship with the primary purpose of transporting passengers or freight. There have been attempts to arrive at the probable cost, pound for pound, of harvesting protein from plankton as compared with conventional methods, with the finding that the most expensive fish would still be about twenty times cheaper than dried plankton. In the *Journal du Conseil* (a publication of the International Council for the Exploration of the Sea)* Philip Jackson of the Scottish Institute for Seaweed Research concludes that "plankton harvesting could not be economically feasible unless and until areas of greatly increased population density can be either located or produced by artificial means, or a radically novel and cheaper method of harvesting becomes available."†

Clearly, then, we must continue to rely on taking larger units of living material from the sea—from the size of herrings up to whale size—after they have accomplished the task of concentrating the minute food that we cannot economically gather ourselves. As plankton converters and consumers at the higher levels of the food chain, they amount in total biomass to a mere fraction of that present in the plankton. According to the best estimates of conversion efficiency from link to link—that is, of biomass or energy passed on from one level to the next after the machinery of living organisms has been kept going—between 10 and 15 percent of the total may be recovered. Thus a hundred pounds of phytoplankton eventually yield only a few pounds of the so-called second-level carnivorous fish (Fig. 27).

Consideration has been given to the possible fertilization of the high seas, with the aim of first increasing the plankton and then, link by link, the mass of larger animals. Once again, estimates of probable cost have been made. For example, to

* *Journal du Conseil*, XX (2): 167–174, 1954.

† The most likely candidate for a breakthrough here would be antarctic krill, the preferred food of certain whales. Not only are the euphausiid shrimp that make up krill about the size of ordinary shrimp, but they also occur in incredible numbers. Both Russian and Japanese research vessels have engaged in exploratory fishing for krill; so far neither the problems of catching nor those of turning the catch into food or feed seem to have been solved.

double the nutrient levels of the North Sea, using land-derived fertilizers, during the summer when light would permit a maximum growth of plankton, the cost would be $40,000 per square mile exclusive of transport and labor, whereas the return in terms of fish would be only about $4,000. Clearly, once again the proposal is ruled out by the prohibitive cost.

Mid-depth and the Ocean Floor

If plankton cannot be harvested with profit, what about all the ocean life beneath the photic zone? After all, even the new mid-water trawl mentioned in the previous chapter can extend our fishing prowess, at best only to a depth of about 200 meters, or 650 feet. That depth, the average of the continental shelf, represents only 5 percent of the average ocean depth. Many net hauls, thus far almost all from scientific research vessels, have been taken much deeper than that. The technique of hauling up nets with miles of wire may be inefficient, and more samples must be taken from the increasing number of submersible vessels that permit explorers to see what they are catching. Enough is now known of life beneath the photic zone, however, to suggest that, even though life occurs in the deepest ocean trenches, there are probably few aggregates of animals that could contribute to the supply of food for human beings. The reason why there are no stocks of fish or shellfish to be harvested from deep waters—leaving aside all nautical and technical difficulties—has to do, once again, with the distribution of light in the sea. But since the annals of mid-depth and the deep sea are unknown to all but the scientists who gather them, it will be of interest to make a short excursion into their natural history, ecology, and distribution, before proceeding to an assessment of the total potential harvest of the seas.

By around 1830 luminous fish had been taken at the surface in the Strait of Messina, where strong tidal currents produce

whirlpools that were already famous in the days of ancient Greece; Ulysses knew he had to beware of the rock of Scylla and Charybdis, as the swirl was called. Although the report of luminous fish made little impact on the scientific world of the time, there is now no doubt that they came from the mid-depth.

The tales of fishermen whose deep setlines had taken angler-fish with stomachs so distensible that they could swallow a prey several times their own size, were likewise ignored by science. But now many mid-depth fish have been caught that show the same adaption to a scarcity of food in a realm where there may be long intervals between meals. For centuries tunny have been taken off the Madeira Isles at a depth of about 200 meters. Occasionally there would also be a slim, ferocious-looking fish, five feet long, with silvery, iridescent sides and daggerlike backward-folding teeth (Fig. 38). This was *Alepisaurus ferox,* one of the larger deep-water predators. Though it is a nuisance to fishermen, the stomach of this fish has proved a veritable treasure trove for specimens of deep-sea fish, including its own kind. *Alepisaurus* probably hunts at a greater depth than that of its capture, and thus at a level where early naturalists assumed there was no life at all.

Toward the middle of the nineteenth century several deep-water dredgings almost to 2,000 meters were made, and living organisms were found in all of them. Yet the British biologist Edward Forbes still maintained that no organisms existed below 550 meters and continued to describe the deep ocean reaches as a lifeless or "azoic" zone. Scientists, doubting that the dredged-up animals really came from such depths, argued for their accidental capture in shallower water—until on a transatlantic cable brought up for repair in 1860 living mollusks and other invertebrates were found which clearly came from depths of 2,000 meters on the ocean floor, where the cable had lain. The *Challenger* expedition (see Introduction) definitely

H. West

Fig. 38. Head of a mid-depth high-seas predator, the slim handsaw fish (*Alepisaurus ferox*). The teeth are hinged and fold in the direction of prey being swallowed but offer resistance the other way. This particular fish caught off Bermuda was almost five feet long.

showed that life existed throughout all levels of the sea, though *Challenger*'s gear was not yet able to explore the great ocean depths.

The hauls made by *Challenger*, and by many research vessels that followed, proved that mid-depth fishes are delicate. Their scales are easily lost and they panic in strong light. They could be ladled out of the experimental townet with small catchers—plastic cages on poles, with an inner lining of perforated sheet plastic that provides the fish with a water cushion

as they dart against their prison wall. The idea of the plastic liner and water cushion can be applied with profit to the holding aquaria as well. But, though nets are usually emptied with as much caution as possible, the fish are inevitably exposed to the air, and they are also chafed and bumped about. In addition, those that live in or near the thermocline experience a shock upon being exposed to a much warmer temperature in the surface water and to an unaccustomed light intensity if the haul is made during the day.

Some of the fish in the haul may be of the rapidly migrating kind that make up the scattering layer. Others may be restricted to one depth, and the sudden reduction in pressure experienced during a confined, relatively rapid journey to a condition beyond their powers of adjustment may cause them to bloat. Even when placed in ice-cooled sea water immediately after their capture, in an attempt to relieve the thermal stress, few of these fish survive for more than a day or two, and none have ever been observed in aquaria long enough to reveal much about their habits. Likewise, bathyscaphe excursions are still too rare to have furnished sustained observations of the behavior of mid-depth animals. What is known about them comes from the examination of preserved specimens, from the clues offered by their anatomy, and from a few glimpses of specimens removed from the net while they were still alive.

Lantern fish studded with light organs are brought up in every haul; so are hatchetfish with luminous flanks, the light organs arranged on their undersides like a series of portholes (Fig. 39), and large eyes set to look forward and upward instead of sideways. The light organs of these fish function somewhat like those of fireflies; probably they help the sexes to recognize each other and may also serve as attractants for prey. The nets usually bring up a few viperfish, sleek, black, and scaleless, with unpaired fins clustered near the tail, and again with small luminous spots on their sides. Some display a yellow-

Brauer, Die Tiefseefische, *Erg. d. Deutschen Tiefsee Expedition, 1898–1899*

Fig. 39. Luminous mid-depth fish. *Top: Astronesthes Martensii,* about two inches long. *Bottom: Stomias valdiviae,* about three and one-half inches long. Both are members of the family of deep-sea scaly dragonfish.

green and others a purple glow in the light organ close to the eye. The salient feature of the viperfish is a huge mouth with long, sharp, saber-like teeth that bend backwards but lock in an upright position. Inside the mouth are luminous patches and a long trailing barbel with a light lure at the end. The bristlemouth fish, one or two inches long, also display living light on their undersides, and have deep-jawed, gaping mouths fringed with the fine, sharp teeth to give them their name.

Transparent, wormlike animals are turned up in many experimental catches. From their eyes, obviously those of vertebrates, and their fishlike fins they are clearly the larvae of mid-depth fish, even though many have not yet been matched with their adult progenitors. Some, indeed, have been described as separate species. Many shrimp, mostly scarlet but sometimes partly bright red and partly transparent, also are caught along with small, stubby-tentacled squid with large light patches on their sides.

The fish in such hauls rarely exceed a length of four inches, and most of them are smaller. A foot-long mid-depth fish is, in fact, a prize, and any haul including a viperfish of that length would be considered to have been a great success.

The small size of fish in these hauls may seem puzzling but is hardly unexpected. For one thing, even in the surface waters there are far more species of small fish, measuring no more than four inches or so—a fact to be kept well in mind when considering the potential fisheries of the world. In addition, the nature of the catching device itself has to be taken into account. Mid-water nets permitting hauls deeper than a thousand feet are small, rarely exceeding a 10-foot aperture, and experimental bottom trawls that require the playing out of several miles of steel cable seldom have more than a 6-foot beam. Also, the vessel moves slowly, rarely faster than a knot, so that even a feeble swimmer of any size could easily avoid the net.

Much larger mid-depth animals than those habitually caught are known to exist, among them the giant squid, whose size has been somewhat overstated by Jules Verne and his successors in Hollywood, the 5-foot lancetfish that are occasionally brought up on deep lines, and the deep-water sharks that have been caught at 600 fathoms (over 3,600 feet). Yet the limited capability of the collecting nets probably only moderately distorts the number and proportionate size of animals in the twilight zone—the huge shark filmed by Cousteau at 1,000 feet in the Red Sea and others captured on deeply set hooks, notwithstanding.

The main reason for the relatively small size of most species and for an obvious decline in their numbers below 1,000 meters (3,000 feet) as one leaves the mesopelagic or mid-depth region is a scarcity of food.* Plants hardly grow beyond the

* Marine biologists have delimited the regions of the ocean floor, or benthic realm (from the Greek *benthos*—ocean bottom), into some more or less separable subdivisions ecologically. The littoral which we have already mentioned has often been split into two zones, the eulittoral (*eu*—true, good, in Greek),

upper 100 meters, and while the plankton algae, as they sink, supply food for grazers low in the food pyramid—the group ecologists call the primary consumers—the number of algal cells still present below 200 meters is less than 1 percent of the bulk that occurs in the photic zone.

Relatively few of the algae that sink out of the photic zone and down to 1,000 meters are decomposed by bacteria; of the rest, the majority have already been eaten while they were in the upper layers of the sea. This competition explains why the animals of the scattering layers make diurnal migrations into the upper pelagic zone. The scattering layers also have their predators—small fish with huge mouths, large teeth, and various lurelike adaptations. Under the conditions that prevail below the photic or production zone—for some mid-depth forms do not migrate upward at night but await the descent of those that do in order to go on preying on them—one can hardly expect to find many large animals.

Between 1,000 and 4,000 meters, in the bathypelagic zone of permanent darkness, conditions become still less favorable for life. The fish found there so far show extreme adaptations to poor feeding conditions. In several species the amount of bone is minimal and the muscles are of a flabby consistency; bathyscaphe observations showed that these fish are lethargic, moving about very little as compared to actively darting species of the mesopelagic zone. They probably feed on small shrimplike

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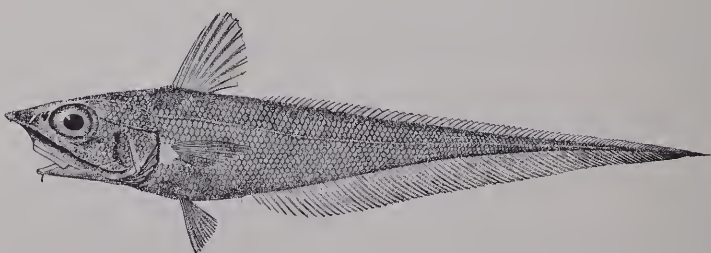
from the high spring-tide levels to the lower limit of where attached plants may grow—rarely deeper than 200 feet—and the sublittoral below, i.e., down to the edge of the continental shelf, at around 200 meters (600 feet). Since inshore waters are more turbid than oceanic waters, marine twilight begins in the sublittoral, and light frequently almost vanishes at its lower borders even at midday. There is no vegetation.

The mid-depth region of the open sea is called mesopelagic (*meso* in Greek—mid or middle; *pelagos*—sea): beneath it is the bathypelagic realm. Extending on the bottom from the sublittoral, down the continental slope to the abyssal plain, which has an average depth of about 12,000 feet, lie the bathyal (*bathos*—depth) and abyssal regions. Finally, there is the hadal realm from (Hades) of the deep open trenches, down to more than 36,000 feet.

creatures which in turn sustain themselves on unicellular organisms somewhat like algae but lacking in chlorophyll. Recent deep samples taken in the Mediterranean and the Atlantic on cruises by a University of Rhode Island research vessel showed these one-celled creatures to be unexpectedly abundant even down to several thousand meters, though still far below the density of plankton at the surface. At such a depth the only possible food would be the dissolved organic material in the water. On the ocean bottom, however, there are again concentrated sources of food for fish, consisting of invertebrates that can subsist on the accumulation of organic matter that for aeons has slowly rained down from above, and larger and more active fish, along with other animals, are found there.

At a thousand meters down the continental slope, where the bathyal or deep-sea bottom fauna begin, the rat-tailed fish or grenadiers are prominent—creatures distinguished by a long tapering tail and a snout that usually has a pointed, helmlike extension (Fig. 40), and related to the cod family, which is so prevalent in the upper bathyal zone. Bottom fish caught be-



Goode and Bean, Oceanic Ichthyology

Fig. 40. This near foot-long member of the grenadier family (also called rat-tails), *Coelorhynchus carminatus*, was caught in the North Atlantic by the U.S. Government research vessel *Fish Hawk* in the last decade of the nineteenth century.

tween 500 and 1,000 meters, like those caught in open water, rarely exceed a foot in length; farther down, the average becomes even smaller. Their shape indicates that they are not very good swimmers. Few have the broad tails that enable surface fish to propel themselves at high speeds, and some are ventrally flattened so as to lie on the bottom. On the other hand, many have large, well-developed eyes, which suggest that they may pursue luminous smaller animals or make regular forays into lower reaches of the twilight zone. Many bathyal and hadal fishes have barbels and/or filamentous fins comparable to the fingerlike fin rays of the sea robin and hake (Fig. 1). Presumably these organs are studded with organs of touch and taste that help them in scouring the bottom for food.

Another set of sense organs, the lateral line system, is better developed in deep-sea fish than in their relatives of the littoral zones. The lateral line, which is peculiar to fishes and water-dwelling amphibians, consists of patches of sensory tissue with hairlike extensions set in little tufts of gelatinous material along an open or pore-bearing canal. On deep-sea and cave fish—which also live in permanent darkness—there may be many thousands of such patches, placed mainly on the head. Even the faintest current of water will cause a bending of the sensory hairs—an action roughly analogous to that of sound on the hair cells in the cochlea of the human inner ear—and thus the fish can sense the presence of a moving prey. The Dutch physiologist Sven Dijkgraaf, who has made a special study of the lateral line, has described it as performing in the manner of a "touch sense at a distance." A swimming object, or any obstacle to the swimming fish, is pinpointed exactly by the hair cells, which are so arranged that they trigger different impulses according to whether water is displaced toward or away from the fish. In deep-sea fish the system is so amplified that a large predator may sense moving prey from a distance of 50 feet or more. In fact, according to Willem von Bergjejk of the Bell

Telephone Laboratories, who has studied the lateral line because of its possible implications for the communications industry, its sensitivity is limited only by the random movements of water molecules, which set up a low-level "noise."

Many bathyal, abyssal, and hadal fish have swim bladders that may permit them to hover effortlessly over the bottom, but that also function both as drumlike sound-producing organs and, incidentally, as diaphragms for the reception of sound. Most rat-tailed fish have extremely well-developed muscles attached to their swim bladders, so that they can produce reverberating sounds in the manner of hide-covered string instruments when the string is made to vibrate. The development of sound organs in deep-sea fish is not surprising, since sound travels farther and faster in water than on land (thus the success of echo sounding) and so becomes a most effective distance signal.

Much of our knowledge of deep-sea bottom life comes from the voyage in 1950–1952 of the Danish research vessel *Galathea,* whose scientific crew dredged in the deepest ocean trenches. A book about the voyage, *The Galathea Deep Sea Expedition,* edited by its chief scientist, the late Anton Bruun, makes truly exciting reading. It also gives the clear impression that the most important item in the vessel's store of modern tools for deep-sea exploration was a winch that deployed a thin, tapering steel cable, 12 kilometers (or 7.5 miles) long, with a breaking strength of several tons at the thin end, for hauling up the deep trawl's bottom grabs or dredges.

These dredges raised, along with the bathyal fish, all manner of bottom invertebrates: deep-sea gorgonians, relatives of the delicate purple sea fans found on shallow reefs; filter-feeding sponges; sea stars with many slender arms; a variety of snails and other mollusks; sea cucumbers; and crustaceans that included bright red crabs and blind, white relatives of the lobster.

There is no sharp dividing line between the bathyal and abyssal zones. Generally, however, the deeper the dredge haul the fewer and smaller the animals, and in some the more remote their resemblance to those of the surface. Among those of the deepest haul were several sea cucumbers, all less than an inch long; there were minute mollusks, worms and shrimplike animals, some of them white like their distant relatives that live in the waters of dark caves. The *Galathea* made a sufficient number of dredge hauls so that comparisons according to depth between numbers of organisms per square meter became possible.

Only a few of the twenty-eight very deep hauls contained no animals at all. Some were described, in fact, as "astonishingly rich," though the yield in numbers and weights of animals varied from a hundred to a thousand times less than for shallower regions. In fact, food conditions in the bathyal and abyssal zones may not be so poor as scientists were once inclined to think. There are probable accumulations of deep-water bottom animals, as a result of peculiar current patterns, that may explain the occurrence of such creatures as the giant squid at a suspected depth of several thousand meters. There are also photographs taken in waters off southern California at 2,000 meters, showing fish estimated to be 20 and 30 feet long. One such fish has been sighted at 1,300 meters from a *Deepstar* submersible. Scientists at the Scripps Institute of Oceanography in La Jolla, in whose vicinity these events occurred, believe that these are large sharks, native to Arctic waters, which must go deep in order to be comfortable off the coast of California. Whether they feed on large surface animals that have sunk to the bottom, or whether perhaps, the dives and photographic stations had intercepted the path of their migration remains uncertain, but they must be fairly numerous or they would hardly have crossed the paths both of an underwater camera and of a lone submersible.

There is also evidence that plankton may be denser in some deep places than was hitherto suspected. Since they receive no light, the organisms that compose it must sustain themselves by taking in the dissolved or particulate nonliving organic matter that is always present. Even taking these reports into consideration, however, conditions in the surface layer remain many times more favorable for life than those that prevail in the depths.

Russian scientists have estimated that over four fifths of all the living material in the sea occurs in the top 200 meters; in the region extending from there to 3,000 meters is found 16 percent of the biomass, whereas the region below 3,000 meters —lying under 77 percent of the sea's total surface—produces no plants and less than 1 percent of the sea's total population of animals. In the future the percentages below 200 meters may have to be revised slightly upward, but the over-all picture will probably remain unchanged. Thus conditions in the abyss far below the photic zone are undoubtedly too unfavorable to encourage hope of exploitation for food.

The Potential Harvest

Calculations of the biomass in the photic zone of the sea—that is, the weight of all the organisms living there at any one time—as well as estimates of what the sea can produce in a year must begin with photosynthesis. There is also required a detailed knowledge of the feeding habits of the animals in all subsequent links of the food web. There is little need to stress again that we are too far from that knowledge at this time to make more than educated guesses. For the present discussion, however, only part of that vast array of sea animals needs to be taken into account—namely, those that, for reasons of location, size, schooling habits, etc., are amenable to exploitation by

man. These are mainly fish, of which it may be said in general that they show catholic propensities and consume a variety of foods. The herbivores take in tiny animals that are attached to their algal fare; others that habitually eat small crabs or worms occasionally browse on the tips of young attached algae. It is therefore difficult to assign any one species to a definite level in the food pyramid. But if it is assumed, for the sake of simplicity, that the bulk of marine fish are first-stage carnivores—that is, they feed on the animals that feed on the phytoplankton—and are thus two steps removed from photosynthesis, they then represent 1.0 percent to 1.5 percent of the plankton biomass. According to the present rather rough estimates of the organic material produced in the photic realm of the ocean, and to the best available information on the feeding relations of many marine organisms, the yearly renewed biomass of first-stage carnivores, only some of which are fish, amounts to probably not less than a billion metric tons, or twenty times the present harvest.

But this seemingly enormous weight of animal flesh includes many creatures too small to be harvested, such as the legions of sargassum fish that hide in the patches of floating algae all over the tropical seas, and others, such as the blennies, morays, and crabs of reefs and rock, that occupy niches inaccessible to man. The total includes the young of the year, as well as all the totally unwanted predators and unpalatable species. It includes those individuals that would have to be preserved if there is to be any harvest in later years. Furthermore, only certain kinds of fish and shellfish lend themselves to efficient harvesting—notably those that swim in schools, such as the herrings, sardines, and anchovies, as well as the tuna and salmon with several second- and third-stage rather than first-stage carnivores among them. Not even the most modern techniques of fish concentration and containment—electric currents, electric lights, or curtains of air bubbles released from hoses laid on the sea bottom—

take all the fish there are in any one area. Many are first removed by predators other than man.

It should be noted here that since 1960 the world fish catch has decreased, for the first time in twenty years; notably, the stocks off Peru and those in the Arctic Ocean have yielded a smaller harvest than before. The next few years will tell whether or not these areas have been fished too heavily.

In the 1967 report of the President's Scientific Advisory Committee on the World Food Supply, one finds widely varying estimates of the sea's total potential harvest. Optimistic scientists speak of 500 million metric tons or more, while others think we may, with luck, double our present take. The correct figure is likely to lie somewhere in between, around 200 million metric tons or so of all manner of creatures, from the tiny prawn to the mighty whale. If this is indeed the limit of ocean hunting and gathering, we do not know whether it can be reached in time to keep pace with the fourfold increase in world population that is almost certainly imminent.

We may indeed hope that it can be reached sooner, since world protein needs increase more sharply with every passing year. In the effort to expand the world's fisheries, new stocks will be sought by exploratory fishing. Those selected should belong to the herbivorous or at least the plankton-eating species, so as to depart as little as possible from the plant base and the greatest biomass. Luckily, most plankton eaters are of the schooling kind—clearly an advantage when it comes to devising new means for their capture.

Better processing also will contribute to enlarging the usable catch. Professor Walter Schmitt of Chicago, who recently examined the planetary food potential from a theoretical point of view, has said that "agriculture and fisheries produce now about 120 percent of the human population's protein and food energy requirements in original quantities (that is, in the raw), but harvest-to-mouth losses leave only about 85 percent of

requirements as consumable quantities." Such losses, which lead to the observable global food deficit, are particularly great in the fishing industry. Processing at sea, and the use of hitherto discarded parts for making fish meal or fish protein concentrates, would go a long way toward increased yield without a commensurable increase in the harvest.

When all these steps, and others not specifically mentioned, have been taken, and when the wild animals of the sea have been exploited at the highest rate permissible if serious depletion is to be avoided, what else can be done to increase the yield? Clearly, man must do in the sea what he has done on land, and what he has now begun to do in fresh and brackish water: he must engage in marine animal husbandry. This kind of aquaculture is seen by many as being the most promising of several potential developments in the marine realm. Captain Cousteau has said that he would seriously think of leasing an area of the sea bottom for that purpose if he were years younger and "had it to do all over again." It may be instructive, therefore, to eavesdrop on some young sea farmers of the future.

Underwater Husbandry

"Tomorrow I've got to clean the bubble curtain hose, the one in front of the octopus-breeding pots on the south face of the reef. Those grunts have been stealing babies again." Such might be the beginning of an evening conversation between two men in a shallow undersea dwelling in the Pacific.

The pots to which our undersea farmer refers would be of earthenware, arranged in tiers, to afford protection to female octopuses for depositing their eggs, the hose would be of plastic, pierced with tiny holes and connected to the air supply of the undersea house, for the purpose of sending out a curtain-like stream of bubbles so as to keep predatory fish away from

the site. The concern would be one common to farmers of all times—namely, the protection of the young in their flock from roaming predators with strong teeth and a healthy appetite. If anything, the submarine herdsman can expect a harder time than his terrestrial counterparts, since such predators are more prevalent on the reef than they ever were on any land-based farms.

The two men might go on to discuss ways to improve the training of half-tame porpoises to corral schools of jack or mackerel, and perhaps end up exchanging reminiscences of a weekend topside, in a floating city some distance away. In all likelihood the two young mariculturists would have leased their farmsite from an international agency charged with the development of marine food resources. Within a few days, perhaps, they might be expecting the arrival of a helper, a diving farmhand, whose year of international service between high school and college is to be spent under the sea.

The dome-shaped sea hut, an outgrowth of the undersea laboratories of the mid-twentieth century, would be a comfortable place, one of several in a settlement a few miles square, inhabited by young people from all over the world. Each would be a self-sufficient unit, served perhaps at four-week intervals by a tender that would replenish the fuel, check on the machinery that supplied air from an intake on one of the reef pinnacles overhead, and clean the combined waste disposal and drinking water facilities. A grille about each entrance would keep off sharks, reinforcing the automatically controlled repellents that would be released in a trickle about the periphery of the settlement. The inhabitants would exchange frequent visits, traveling on air-driven underwater sleds, to plan and coordinate their work, or to gather, perhaps, for an evening of twenty-first century rock 'n' roll.

The colony would specialize in raising choice seafood, including octopus and rock lobster. They would also tend algae

for drug extraction and large pearl oysters, coaxing them to produce gems of particular beauty. Raising finny fish from underwater bases would not, at least in the tropics, have proved economical; the basic cost and upkeep of the installation would have been too high, as compared with fish ranching from the surface. Only certain more or less sedentary invertebrates can be grown at a profit.

Farming Stock

The branch of agriculture that deals with animal husbandry proceeds by the selection of suitable strains, the improvement of habitat, and a selective harvest at suitable times. The development of agriculture as a whole has meant increasing human control over parts of nature. Very early in history the cultivators of Egypt and China included both water and land animals in their husbandry. Fresh-water fish and shellfish were grown, possibly in rivers and lakes and certainly in ponds, where principles of terrestrial farming were translated into aquaculture.

Ponds are quite easily manageable, when compared to lakes and sheltered bays of the sea. It is therefore not surprising that true animal husbandry with sea life had hardly been attempted until recently. Judging from the recent development of mariculture along many coasts, however, it would appear that terrestrial man may soon be using the sea in many more ways than have hitherto been possible.

Fish, a class of vertebrates allied to mammals—and thus to ourselves—are relative newcomers on the evolutionary scene. They arose in a sea that was filled with invertebrate life some 350 or 400 million years ago. Marine invertebrates are many times more numerous than their descendants the fish, both in numbers of species and in living weight or biomass. Yet the take of fishes far exceeds that of their more primitive cousins.

Only two groups of animals without backbones—the crustaceans and the mollusks—contribute in any degree to the harvest of the sea. Both are encased in hard covers or "shells"—though of different kinds. Hence the word "shellfish," a misnomer since neither one is a fish and the only real similarity between the two is that both share the same watery world and are fed on by some of the same fish.

Crustaceans—shrimps, lobsters, and crabs—are arthropods or joint-footed animals, whose external skeleton provides attachments for the muscles as well as protection. They are fairly closely related to insects, and are comparable to them in complexity, variety, and distribution. Mollusks—oysters, clams, and squids—are predominantly an aquatic phylum. They are in many ways more primitive than the crustaceans, and made their appearance on earth hundreds of millions of years before them. As a whole, the shellfish surprisingly contribute less than 10 percent to the total aquatic world harvest; shrimp, king crab, squid, and oysters are the leading kinds, and the several hundred thousand other species are hardly harvested at all. Most often this is because the latter are too small, and many of them, such as the barnacles, are so firmly attached that the effort to take them is in no way commensurate with the return. Other invertebrates, including the comb jellies among the plankton, are too watery; still others, including many of the bristleworms, as well as numerous mollusks, burrow so deeply that the effort to secure their meat would once again be out of proportion to the result.

To be caught or gathered efficiently and economically, aquatic animals should come in large chunks that are close together. Most commercial fish answer this description—all the way from tuna, which make up in size for what their schools lack in numbers, down to the much smaller herring, whose shoals may contain millions of individuals and are so dense that the herring under the surface of an acre of water would weigh

7,000 pounds or more if they were all scooped up together. Clearly, fishing pays under such circumstances; indeed, the only way of making the land yield proteins that comes close to nature's herring factory is to grow broiler chickens by assembly-line methods—in which, incidentally, much of their food would be derived from the herring.

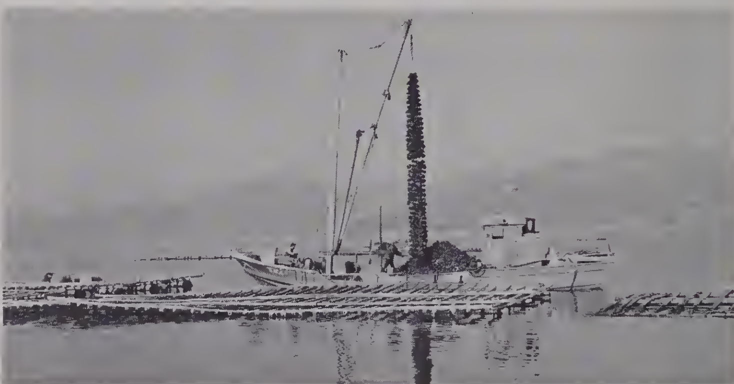
There are shellfish, though, that can give higher yields to the acre than most land animals—namely, oysters, mussels, and the like. These mollusks are among the oldest food of man, as many prehistoric kitchen middens testify. In fact, Carl Sauer, the University of Chicago geographer, believes that those tribes of early men who settled in coastal regions where mollusks abounded made more rapid progress on the road to civilization than their game-hunting inland cousins, who had to expend much more energy in securing their proteins. Millennia later, but very early in recorded history, men started to cultivate rather than merely to gather oysters and other bivalves; indeed, as Pliny reported, by Roman times they were well on their way to oyster farming, and they have improved and intensified the practice since.

Oyster Culture

Oysters lend themselves particularly well to intensive management, since they are sessile animals that thrive in the brackish, shallow water of estuaries, close to shore. It is possible to improve their habitat, to provide places of attachment for their free-swimming larvae, to combat such enemies as starfish, oyster drills, and certain fungi and bacteria, and to transplant the oysters themselves from the nurseries to better growing grounds simply by broadcasting them into the water. For certain highly esteemed culinary strains, it is possible, as the French have proved, even to raise special algal food on

which the oysters grow fat and green. The oyster is probably the most thoroughly domesticated marine organism to date. Its life habits make it particularly amenable to control by man—in other words, to true aquaculture—and it gives a high yield of protein, fats, and carbohydrates as well.

The world's most advanced oyster culture is practiced near Hiroshima, among the bays and inlets of Japan's Inland Sea. These lovely, island-filled waters enjoy just enough river inflow to give the right mineral content, making the sea rich in plankton and producing ideal conditions for oysters. Since oyster larvae attach themselves to a hard substrate, the main principle of oyster growing is to provide their young with more such places than nature itself provides. So the bays of the Inland Sea are covered with bamboo rafts that float on barrels (Fig. 41). From the bamboo frames wires hang into the water



Japan Inland Sea Regional Fisheries Laboratory

Fig. 41. Harvesting the crop of oysters on Hiroshima Bay. The rafts carry wire-suspended clamshells on which the oysters grow. The tiers of shells are hanging on the boom and the oysters are heaped aboard.

to a depth of 20 feet or more. Strung on these wires are clean clamshells held apart by short lengths of thin, hollow bamboo. During July and August, when the oysters spawn, billions of their larvae attach themselves to these shells; they are so dense that they must soon be thinned out to avoid crowding.

On the rafts oysterwomen work under parasols, culling larvae from the shells to the proper density and lengthening the intervals between the shells by replacing the original short bamboo spacers with longer ones. Later in the season each of the wires is pulled up again and the young oysters are cleaned with brushes and water jets so as to rid them of algae and to make their life easier still while they attend to filtering the plankton over their gills and into their gullets, all the while growing rapidly. Depending on the temperature and the density of the plankton, before the harvest the rafts may even be towed to pasture in some other part of the Inland Sea.

The standard raft—of which one grower may have a hundred or more—measures about 30 by 45 feet. At spawning time it is supported by 18 barrels, but as the oysters grow the raft sinks and new barrels have to be added. Before the first harvest, in January or February, a raft may require 40 barrels to keep it afloat. The oysters turn plankton algae into their savory flesh at such a rate that one raft may yield two metric tons of shucked oysters in a year. This amounts to more than 13,000 pounds of oyster flesh per acre, a yield reached on land only with the most intensive animal husbandry practices and certainly never without much costly additional feeding.

The keys to this success are, first, the use of the water through much of its depth and, second, the intensive care given to the growing oysters. Another dividend of raft culture is the foiling of some oyster predators. Since oysters are originally bottom dwellers, many of their predators likewise stay close to the sea bed. A starfish, for instance, crawls over the oysters,

attaches its suction-padded tube feet to the tightly closed shell and eventually forces it open. Then it everts its stomach into the oyster and cleans out the shell. Starfish cannot swim, however, and since the wires do not reach the bottom of the bay, they are no menace in raft culture.

The harvesting of oysters is simple, too. Though many Japanese oysters are hand-picked, scoops, tongues, and dredges usually suffice. What is more, the boats used in this pursuit need not be large, nor are they built for the high seas and therefore expensive. It is not only the oyster's flesh that is used; in addition, their shells are made into "poultry grit" or serve for the manufacture of a high-grade lime that is used in various industrial processes and as fertilizer.

Other oyster-growing nations, whose labor costs are higher, can go only part way toward emulating the Hiroshima Bay oyster farmer. The growers usually provide for the larvae some less elaborate attachment—commonly known as "culch"—for example, by broadcasting empty oyster shells over suitable stretches of bottom, by planting poles, by submerging tiles or limed egg crates, and so on. The United States, because of its natural endowment with bays and inlets along both east and west coasts, was once by far the greatest oyster producer in the world. These resources have been dwindling, for reasons that will be given presently, and Japan, which now produces 77 million pounds of oyster flesh per year, has outstripped America.

When a farmer owns his land and passes it on to his son, whatever improvements he makes on it will be of benefit to him and his family. Oyster grounds are like fertile land; they need to be tended and protected, and they can be improved. If oyster grounds are maintained in the public domain and the animals are treated as a common resource that is open to picking by everyone, the beds become depleted. Dr. Paul Galtsoff, probably the world's chief authority on oysters,

writes: "Century old experience in the state maintenance of public reefs shows that self rehabilitation of grounds without active assistance from man is incompatible with intensive commercial exploitation. The enactment of conservation laws, such as closed seasons, size limits, restriction of gear, etc., has been ineffective in stopping depletion." These two sentences apply to the public oyster grounds of Maryland. In Virginia, across the bay from Maryland, oyster reefs have been leased to private growers, with some assurance of perpetuity, and oyster production has steadily increased. As we shall see, there is a lesson here for the management of other marine resources.

Through aeons of evolution, the oyster's many parasitic enemies have developed effective means of destroying their host. But effective as these predators may have been, man is now the oyster's greatest enemy. The story is the same in all the principal oyster countries—in Holland, in France, and in Great Britain, but most of all in Japan and the United States. The east coast of North America is particularly blessed with shallow bays and estuaries, such as Chesapeake Bay. Here until recently the sessile oyster thrived, finding proper substrate and rich plankton pastures from which to filter diatoms and other algae. Oysters live where rivers meet the sea, and since they cannot move they are exposed to any polluting chemicals that the rivers may contain. They can be poisoned directly; they can be silted in by an excess of sediment in the water; and they can be affected by sewage, detergents, and insecticides. They may not be destroyed outright, but if they are weakened, not only are they more liable to succumb to disease and parasites but their larvae are less likely to survive. Even if the oysters are healthy, those growing in a steady stream of poorly treated sewage may retain pathogenic bacteria from the filtered water, both in their guts and on the mucus of their gills, thus becoming a health hazard and a

prime exhibit in the case against river and estuarine pollution—a subject to be treated in more detail in the last chapter.

Pearl Farming

Animal flesh is by far the most important material man obtains from the sea, but there are also such products of marine commerce as the skins of the hunted animals; extracts and powders made for industrial use from the leaves and stems of algae; buttons from the shells of mollusks, and coral jewelry, to mention only a few. Perhaps the most romantic and beautiful of all such nonedible products are pearls.

Many bivalve mollusks, when a sand grain somehow finds its way onto or under the edge of the soft membranous lining of the shell—called the mantle—react to the irritant by surrounding it with layers of nacre, the hard, iridescent material that lines the interior of the shell. Many mussels and oysters produce pearls, some more consistently than others. In the past the value of pearls was a consequence of their rarity, even though some regions—such as the Persian Gulf, the waters around Japan—and also certain rivers, the Mississippi among them, were known to reward pearl seekers more often than others. Today most of the pearls of commerce are cultured by tricking the pearl oyster—which is not of the same kind that is eaten but a rather distant relative—into secreting nacre around a core of mussel shell that has been deliberately placed inside it.

Some of the practices of tending pearl oysters resemble those for edible oysters. They, too, are suspended into the water from rafts, but in baskets or bags of plastic netting rather than on strung clamshells, and they are cleaned and protected with great care. Marine pearl oysters (mainly of the genus *Pinctada*) are ready to "produce" when they are about two years old. At this time they are raised from the sea, a wooden wedge is placed between the shells to pry them open temporarily, and

the opened oysters are stacked before the worker, who implants the seed for the pearl-to-be. The growing of cultured pearls consists of wrapping a fragment of mussel shell in a sliver of mantle from an oyster sacrificed for the purpose (one oyster serves for approximately twenty implantations). When the piece of mantle and its core of mussel shell are implanted into the gonad cavity of an oyster, the sliver of introduced mantle fuses with the oyster's own tissues and surrounds the core with layer after layer of pearl substance. Depending on the size of the core and of the oyster itself, it receives anywhere from one to four implants. Immediately after the operation, the wedge is withdrawn and the treated oysters are quickly returned to their baskets in the sea. At least two years pass before the pearls are ready to be harvested.

The technique of pearl culture was developed by a Japanese marine biologist, whose father-in-law, Mr. Mikimoto, later patented it (Figs. 42 to 46). The patent has now expired, and many individual pearl growers contribute to Japan's production of cultured pearls, which in itself is worth about $50 million a year. A curious sidelight to all this is that the shells of American fresh-water mussels are exported to Japan, since they provide not simply the best but almost the only available raw material for the cores. The supply of these mussels has dwindled, and they are disappearing from their home streams in the region drained by the Mississippi because of silting and pollution. Yet Americans, with all their affluence, are the main buyers of cultured pearls, thus bringing back home a fragment of mussel shell from some Ozark stream whose value has been greatly increased by its sojourn in Far Eastern waters.

Japan is not the only source of pearls, however. Indeed, some large bivalve species in the tropical Pacific are able to produce truly gigantic pearls in a short time. Natural and cultured pearls cannot be readily told apart; often they can be distinguished from one another only by the use of X rays, which

Author

Fig. 42. Rafts for pearl oysters in a bay near Kashikojima on the Ise Peninsula of Japan.

Tasaki Pearl Co., Kobe, Japan

Fig. 43. Slicing "pieces" of mantle for insertion, together with the "core," into another mussel.

Fig. 44. "Core" and "piece" shown beneath the pried-open mussel, ready to be inserted.

Tasaki Pearl Co., Kobe, Japan

Fig. 45. The pearl inside the mussel is ready for harvest.

Tasaki Pearl Co., Kobe, Japan

Tasaki Pearl Co., Kobe, Japan

Fig. 46. Sorting the pearls.

reveal the core of a cultured pearl as a uniformly opaque image within the onion-like layers of nacre, whereas in a natural pearl the concentric rings go all the way to the center. Imitation pearls, the cheapest of the lot, consist of a very thin layer of nacreous substance extracted from fish scales and sprayed over a plastic sphere. Unlike either natural or cultured pearls, they do not fluoresce, and can thus be readily distinguished.

Raising Shrimp

For some years after World War II the shrimp industry boomed in the Gulf of Mexico. More and more trawling vessels joined the nocturnal hunt for these animals, which bury themselves during the day and emerge at night to feed. Very soon

the take showed a decline. But artificial shrimp husbandry can be practiced, as Dr. Fujinaga, a Japanese pioneer, has demonstrated. Pilot studies aimed at establishing this kind of mariculture are already under way in the Gulf states and eventually they may improve upon the Oriental method.

The world's first successful large-scale shrimp farm is at Ikushima-Cho, a small village on the island of Shikoku. It consists of several acres of shallow ponds, through which filtered sea water is pumped at a rate of more than 500 tons an hour, so as to effect four complete changes daily—clean and plentiful water being one of the prerequisites for successful shrimp culture. A second prerequisite is a supply of berried shrimp—females with eggs attached to their abdomens—which are bought from fishermen at the natural spawning season.

The next stage of shrimp culture is the most difficult. Shrimp (along with many marine fish) undergo several larval stages, during which they are very different from the adults and require an entirely different kind of food. Moreover, they may also inhabit a different layer of the water. Invertebrates, like more complex organisms, recapitulate in their own life history their development as a species. Those that live in the sea have no need in their early life for the uterine or egg-enclosed environment that protects the development of a mammal, bird, or reptile; instead, they begin as free-living larvae. Their first food often consists of either tiny algae or plankton animals, or both. As their anatomy becomes more complex, they develop new or additional mouth parts which make possible another diet. Sometimes the succession of food requirements may include dozens of distinct organisms before the animal settles down to its adult fare—which in its turn may consist of more than one organism.

Thus the mariculturist is required to grow a variety of foods even though he is raising only one species. The early foods of

larval fish and crustaceans consist usually of plankton algae, diatoms, and small crustaceans, all of which are delicate and have special growth requirements: particular trace elements, decomposition products, the secretions of other organisms, and certain biotic factors. It is thus hardly surprising that the production of such larval foods on a large scale has not been very successful. For instance, many years of painstaking experiments were needed to perfect methods of diatom culture by which a uniform supply of plankton could be continuously extracted from the growing medium. It was impossible to grow these yellow-green algae in vats, simply scooping off the surplus as it developed, because the cultures then became extremely variable and liable to self-poisoning as the algal broth grew thick.

Once the young shrimp have been coaxed through some of their larval stages with specially cultured foods, they can be accustomed to a simpler diet, namely, finely minced clam flesh, strained through a hair sieve. Though this is not their natural fare, they accept and thrive on it, so long as they are fed late in the evening and again at night, according to their nocturnal habit. Diseases and parasites, which are often serious obstacles to raising animals in close quarters because of the risk of infection, are less of a problem with shrimp than with fish, birds, or mammals. Shrimp molt repeatedly, and along with the old skins they also discard any disease organisms that may have congregated there in the intermolt period.

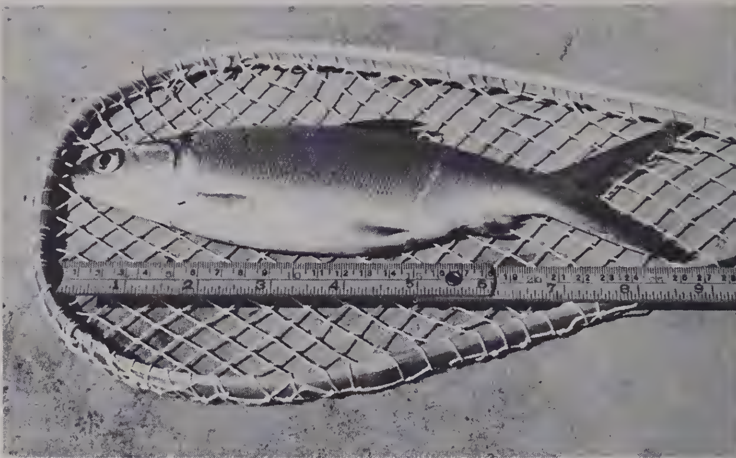
Three hundred million young shrimp are distributed every year from Ikushima-Cho to the smaller shrimp farmers of Japan's Inland Sea, who are without the technical equipment and proficiency to raise them from the egg but who feed and fatten them for the big shrimp season during the winter months. There are now a fair number of shrimp farms in Japan, where the long tradition of obtaining most of the supply of protein from the sea, together with a plentiful supply of cheap

labor, contributed to the success of Dr. Fujinaga's experiments in culturing shrimp. But cheap labor is no longer plentiful in Japan, and shrimp-raising enterprises threaten to become marginal for economic reasons.

It may be possible to raise other crustaceans from the egg; for instance, lobster-hatching experiments by the U.S. Fish and Wildlife Service at its laboratories in Maine were very successful. They have not been developed commercially, however, mainly because lobstermen are small operators with little or no capital. The take per trap has declined, but as a result the price of lobsters has risen sufficiently for lobstermen still to make a living. Because there are a number of substitutes for Maine lobster available on the market, the profits from a lobster farm are not likely to be high enough to make the necessary investment worthwhile. Nevertheless, shrimp farming and the rearing of lobsters in the laboratory suggest that all sorts of marine animals can be husbanded. The success of such an operation depends on the degree to which the habits of the animal in question permit human attention to be replaced by machines. The forms of mariculture that have been tried thus far may be only the beginning. Other such experiments, including the rearing of trout in the sea, will be described in the section that follows.

Fish Rearing

Plant-eating fish would seem to be likelier candidates than carnivorous species for husbandry, provided their food can also be grown. An example is the Asian milkfish, which can live in brackish waters and whose food consists of blue-green algae (Fig. 47A). The precise location of its offshore spawning grounds and the details of its spawning habits are both still unknown. Its husbandry begins, rather, with catching the larvae as they drift along the sandy beaches of Taiwan, In-



Department of Fisheries, Taiwan

Fig. 47*A*. A herbivorous milkfish grown in a brackish water pond in Taiwan.

W. H. Schuster

B. Catching milkfish fry on the shore of Java; the tiny fish are concentrated by the long strings of plant fiber placed perpendicularly to the shore and then scooped up with a net of fine gauze.

W. H. Schuster

C. The fry are taken to boats in clay containers and transported to the ponds.

donesia, and the Philippines, where seining for the young fish is the special occupation of local women (Fig. 47B). The larvae are first placed in shallow ponds and later in deeper ones, whose water level is strictly controlled by sluice gates, and which have been inoculated with cultures of the algae on which the fish feed.

True domestication of the milkfish, including the breeding of superior strains, will only be achieved when the fish can be made to spawn in captivity. Experiments with hormone injections have made other kinds of fish spawn on a man-made schedule; milkfish should respond to such treatment also.

Aside from the relative ease of growing the algae, a further advantage of milkfish culture is that it takes place in areas that

W. H. Schuster

D. Aerial view, close to the seashore, of milkfish ponds in Java.

do not lend themselves to any other use. Many tropical coastlines and estuaries are covered with mangrove swamps that are flooded at high tide and have highly saline soils, unsuitable for agriculture. The mangroves can be cut down and ponds built on the sites. The maintenance of a steady water level by means of channels and gates connected to the partly saline lower rivers is often assigned to the fish farmer's children. They learn to take their job seriously, for a slight drop in the level of the shallow nursery ponds might mean the failure of the entire year's crop. The crop is nevertheless remarkably large, considering that the daily effort required to produce it is so moderate that many milkfish farmers can carry on other occupations.

Even some carnivorous fish offer possibilities for culture, among them sedentary species such as sole and plaice. J. E. Shelbourne of the Fisheries Laboratory at Lowestoft, England, has this to say about raising them:

> The natural diet of the plaice includes small molluscs and marine worms. Mussel (*Mytilus edulis*) culture on a large scale should present no special difficulties; it is not beyond the realms of possibility that a cheap manufactured food based on fish offal or agricultural by-products, with balanced additives, would be acceptable to marine fish in fattening ponds.
>
> Whereas "reaping" the natural stock is the expensive aspect of fishing, as we understand the term, "reaping" a pond stock is the cheapest imaginable process—simply pull out the plug and drain the pond. In this way, really fresh fish would become available to the national market with minimum preservation and processing costs. Processing plant is an expensive investment at the moment, inefficiently operated due to the fickle nature of fish supply. Rotational pond cropping, in a systematic manner, would enable the industry to trim its processing investment to the scale of continuous, guaranteed supply.
>
> As a matter of interest, roughly 200 million North Sea plaice reach marketable size (25 cm.) each year. About 75 per cent of fish entering the fishery are caught by trawlers, the British effort accounting for 25 per cent of the total take. In 1961, for instance, 35 million North Sea plaice were caught by British vessels. If each fish be given a hypothetical allowance of 1 ft^2 of bottom, then the annual British catch could be housed in shallow ponds covering 1¼ square miles in extent.

Although many ifs and buts remain concerning this stage of marine fish culture, ingenious experiments have already been made. One such will be described below.

Trout Assembly Line

Carp and trout may be described as truly domesticated fish. Both have been bred for so long and with such care that there are selected strains and varieties exactly as there are for other domestic stock. These are not marine varieties. Nevertheless,

trout—as relatives of the salmon, which lives part of its life in rivers and part in the ocean—can be acclimated to the sea. Trout reared in hatcheries are now fed on pellets which constitute a uniform and relatively cheap diet. The discovery not only that trout can be raised on an assembly line but also that fish are capable of a Pavlovian reflex that causes them to associate food with signals such as sound or light led a famous Japanese fishery scientist, Dr. H. Uchihashi, to devise an interesting maricultural practice with possibilities for future development.

Trout fingerlings from special fast-growing strains are raised in the usual way in inland hatcheries. Before the onset of winter, which slows their growth, they are brought to the seashore, where over a period of about two weeks their fresh-water environment is gradually changed to a salty one. They are then transferred to an enclosure in a nearby bay for a month's training, which consists of sounding, two minutes before they are to be fed, a particular signal on a wavelength of 400 cycles per second, a frequency the fish are known to perceive acutely. The pellets are fed exactly one minute and thirty seconds after the sound has ceased. While the fish are feeding, the same signal is repeated. The food is dispensed by means of an automatically rotating pellet-broadcasting device, which distributes the pellets farther and more evenly than can be done by hand.

After one month the barrier of the enclosure is removed, and the fish are free to swim about in the bay. When the "food bell" sounds they come crowding in to snap up their share of the pellets, even if they have strayed for some distance in the sea, since the vibration travels rapidly and for a long distance, and since no other pure sound of the same wavelength occurs among the various engine noises to which they may possibly be subjected. The fish can also learn to tell time. After ten days of being fed exactly at noon, they will show that they anticipate the feeding hour by more active swimming and coming to the

"trough." As a result, the trout are usually not far away when the dinner bell sounds. Between automated feedings they may also pick up some morsels as they roam about.

After a few months in the sea, at optimal temperature for their growth, they are large enough to be marketed; catching them then is simply a matter of surrounding them with a seine as they come in to feed. Fish not only respond to timed vibrations but can also distinguish between two adjacent pure tones. Not much imagination is needed to envision future sea farms where selected strains each of several species will be trained to respond to a particular tone at a particular hour and be so conditioned that catching them will be one more simple automated process.

Algae Culture

If shrimp, milkfish, oysters, and some other marine animals grow on plankton algae during all or a part of their lives, and if algae can be grown for them, why not go one step further and culture the algae directly for human consumption? The sun's energy could then be tapped more fully and directly without losing so much of it in the transfer from one step to another in the food chain.

One good reason why there has been no such development is the lack of economic incentive. Assuming that really large-scale alga culture is possible, it would—depending on the method of extraction—either end up with a kind of marine spinach or with a greenish powder, smelling of hay, that would have to be admixed to other foods or otherwise transformed into a product that people would eat. The growing process in itself is expensive, requiring tanks, tubes, mixers, lights, and so on, and it is made more costly still by the need to render the product appetizing. Even then—bearing in mind the resistance, in relief operations, put up against free powdered milk

by people whose habitual diet did not include milk—there still might be no sale.

Another, and perhaps more important, consideration is that those algae that have so far been analyzed lack certain essential amino acids and thus do not provide for a complete diet. Also, rich though they may be in minerals and vitamins, the latter would probably be lost in processing. Moreover, algae are not easily digestible unless their cell walls have been broken down.

Growth requirements are known for relatively few species of algae, most of them strictly fresh-water forms. The marine species are more difficult to tackle, and it is only recently that bacteria-free cultures have been made. The best known and most often used species is *Chlorella,* a small, green, spherical plant, common in lakes and ponds but also capable of being grown in brackish water; perhaps strains can even be developed to be grown in undiluted sea water.

Under favorable conditions *Chlorella* cells divide and grow rapidly. Each cell consists largely of a chlorophyll-bearing chloroplast whose function is to carry on photosynthesis; there is no stem or root for support or the absorption of nutrients. Yields per acre of *Chlorella* can be envisaged that are many times those of today's land crops, of which often only the storage organs, such as seeds or roots, are eaten. Also, the ratio of protein, carbohydrates, and fats in the algae can be manipulated according to the stage of maturity at the time of the harvest. To the expense for special tanks, trays, pipes with mixing valves, and for special lights that will induce continuous cell division and optimum growth, must be added that of extracting algal cells at a uniform rate after the harvest has been made. For this reason one pound of *Chlorella,* wet or dry, at present costs many times more than the same amount of flour, rice, or fish meal.

Green algae, of which *Chlorella* is one, are far less abundant than diatoms in marine plankton. Though these latter have been

investigated less than *Chlorella* and its relatives, they would no doubt pose similar obstacles to large-scale culture. In addition, they have the disadvantage of being covered with a hard, almost glass-like silicious shell that would have to be removed before direct consumption by man could take place. But since they serve as food for many marine animals (see the section on shrimp raising, pages 194–197), they will be grown for that purpose instead. Harvesting the diatom eaters will still be cheaper than it would be to build and operate the installations required to harvest the algae themselves, notwithstanding the large loss in biomass incurred by using a higher link in the food chain.

But there is another use for which algal cultures may well be important in the future. Even now algae and bacteria are used to treat sewage effluents before they enter a stream—the algae to supply oxygen, the bacteria to decompose organic materials. Leaving aside the question of how thoroughly the water is purified in the process, it may be complained that the growth potential of the algae is unused, primarily because the plants are spread over porous sinter beds from which they cannot be removed. If, on the other hand, the algae and bacteria so used were free-floating in shallow ponds, and if they could subsequently be filtered, they might be dried as fodder. An animal feed ingredient from *Chlorella* has already been made under experimental conditions at Berkeley, California.* It is important to note further that the use of brackish water for certain portions of domestic water supply has been considered and that *Chlorella* grows in half-salt, half-fresh water.

The work of sewage disposal under ordinary terrestrial conditions, with later use of the transformed organic matter, could be entrusted to plankton algae. On space platforms and in large space ships *Chlorella* or some similar plant form will certainly be employed for this purpose. Not only would the algae and

* Considering that the same sewage would have to be purified by conventional means with levies charged per unit volume, the *Chlorella* feed could become very cheap.

bacteria transform human wastes into potentially useful substances for space travel, but the waste carbon dioxide produced by human respiration could be fed into a tank where algae would make use of it, along with sunlight and the nutrients from the waste itself, to liberate the oxygen essential for breathing by the process of photosynthesis.

In contrast to the many floating green algae, the red and brown algae of the coastal zone grow on the bottom where light still penetrates or produce air floats that keep their fronds on the surface. Some brown algae in the kelp forests of California and Oregon grow to a length of 300 feet—making them the longest plants known, although it would be incorrect to describe them as the tallest since they trail in the water that supports them rather than stand upright. Compared with plankton algae, they come in man-sized chunks, and the problem of harvesting them lends itself more easily to a technological solution. Some brown algae, such as the *Gelidium* of Japan, from which agar is made, are still hand-gathered by divers, who also tend the growing areas (Fig. 48). Others (such as *Porphyra,* with greenish-brown fronds up to a foot long) are encouraged, during the spore stages, to attach themselves to special frames, which are then placed in the tidelands under suitable growing conditions. Both species are used all over Japan for soups, stews, relishes, and other dishes.*

Still others, such as the largest brown algae—*Macrocystis* and its relatives—are not tended but only harvested, using grapples or even special underwater mowers. These algae rarely are eaten directly except as an ingredient of mincemeat and of jellied fruit substitutes. They are important, however, because of the colloidal electrolytes, or alginates, that are

* Certain of these algae, called laver, or nori in Japanese, contain large amounts of cholesterase, the enzyme that breaks down cholesterol, which is deposited on human blood-vessel walls and leads to hardening of the arteries. Circulatory ailments are less prevalent in Japan than in the United States, a fact that could be coincidental, however, rather than related to laver eating.

Fig. 48. On the island of Myake Jima near Tokyo, girls traditionally dive for red algae of the genus *Gelidium* from which the agar of commerce is made to be used as a bacteriological medium and in the cosmetics and pharmaceutical industries among others.

A. The girls used to wear white cotton shifts, now many use foam rubber diving suits. Their gear consists of a wooden float and nets into which the algae are gathered during the dive that can take them down to 30 or 40 feet.

B. The algae are dried and cleaned.

C. Eventually the algae are bundled for shipment to the mainland where they are to be treated further.

J. Moyer, American School in Japan

extracted from them. Alginates vary in consistency with the metal element that is employed in producing them; they may be soluble, viscous, and tacky, prone to form almost insoluble films, or so totally insoluble as to offer a potential base for commercial plastics. Calcium alginate—to take one example—is insoluble in water but dissolves in an ammonia solution, making it usable as a "vanishing yarn" in weaving very lightweight wool fabrics. The process is as follows: a very fine wool fiber, too fine to be used by itself, is twisted with a strand of calcium alginate, and the combined thread is woven as a fabric. When the weave is passed through an ammonia solution, the alginate dissolves, whereas the wool is unharmed, leaving an almost gossamer-like fabric that weighs only one and a half ounces to the yard.

Still another use to which the solubility of alginates has been put, although still on an experimental basis, is in preparing food for cultured abalones, the tasty marine snails of the Pacific that feed on the algal mats covering rocks and stones. No way of growing this kind of algae has yet been found, and harvesting it to feed the snails has also been impossible. Abalone culture, desirable though it was considered to be, could not be successfully undertaken until a Japanese biochemist thought of mixing fish meal with sodium alginate, wetting the mixture to make a paste that could be spread over glass plates, which were then dipped in a solution of calcium chloride. At this stage of the process the sodium alginate turns into calcium alginate and becomes insoluble, producing a thin, felt-like mat that can be peeled off the glass, cut into strips, and thrown into the tank, where the snails gobble it up. Abalone culture on a large scale may become feasible if and when this method is transferred from the laboratory to the field.

The colloidal nature of some alginates permits them to bind water, giving them jelly-like properties. They are used to give ice cream a smooth consistency, as ingredients in hand and

face lotions, and as a step in the brewing process, to clarify and give body to beer. Many other industrial uses, some pharmaceutical, of the extracts of red and brown algae have been made or are being investigated. Although the harvest of attached algae will no doubt increase in the future, their ecology makes intensive management difficult. Nevertheless, it should be possible to apply certain practices from forestry to large underwater stands of kelp, such as that of leaving certain plants standing for regeneration and reseeding while others are being cut. The impending conquest of the continental shelf by aquanauts and robot equipment (see Chapter 2) should make such management quite feasible. Such developments will, however, remain local, if they become economical at all, because of the limitations of suitable underwater terrain. On a global scale animals as food for man will continue to outweigh algae in importance.

Whether algae or oysters or fish are to be grown, the productivity of certain marine regions may have to be augmented. It has been observed that the application of land-derived fertilizers to the high seas is not practical; the enriching of bays and fiords, however, appears somewhat more promising. After certain lochs in Scotland were fertilized, the plankton crop was doubled or tripled. Experiments with raising the yields of enclosed bays are being continued: Yugoslavian scientists plan to work on bays of the Adriatic Sea, and the University of Strathclyde in Scotland will do a three-year study of advanced civil engineering problems associated with the commercial prospects of intensive fish farming.

In all experiments with fertilization of the sea on any scale larger than in single ponds, the main problem has been the dissipation of nutrients. It may be possible to add to the chemicals inoculates of nitrogen-fixing algae or other fast-growing strains, as is done in milkfish ponds, so as to increase the biomass of primary producers and widen the base of the

food pyramid. But there would still be the inevitable loss of nutrients to the sea at large, though the action of tides and currents, the locking up of nutrients in bottom deposits, and the loss of energy in each of the several steps from sunlight to the fish. These varied obstacles have so far, at least, made the value of any attempt to fertilize the marine environment somewhat doubtful.

Schemes of ocean fertilization on a larger scale, without the direct and costly addition of chemicals, have been envisaged. Since it is known that the upwelling of deep cold waters brings with it rich crops of plankton and all kinds of fish, the argument runs, why not help nature out and produce artificial upwelling? Various means are possible, their nature depending on how far from shore they are to operate. Close to the land, especially where the continental shelf is narrow, it might be feasible to sink pipes carrying waste heat from nuclear reactors or other power plants below the thermocline, so that as the warm water rose it would bring up cool, nutrient-rich water along with it. Farther out at sea a self-contained nuclear reactor might be set at such a depth as to provide the driving force for induced upwelling by means of its waste heat. It is believed that under certain conditions the upwelling requires only a starter, and that it might in fact become self-sustaining. There are still such problems as dissipating currents, though, and these and other schemes, though technically feasible, may not be practical, either because they cost too much or because of unwanted side effects. Several river environments, for example, have undergone harmful and unwanted changes as a by-product of nuclear power plants, but even if the unwanted heat could be used to good purpose, it might be that radioactive wastes would negate any benefits. Also, sites suitable for induced upwelling are few, and are strictly limited because of salinity and temperature conditions. Moreover, if the process could be set in motion, it might have adverse side effects on the climate of the region.

Large-scale "weeding"—that is, suppression of inedible species—should not be overlooked in considering ways to boost productivity. Unfortunately, since "weed" species are presumed to play an important role in the ecology of the sea, we cannot be sure whether eliminating them though costly would have the desired effects or might backfire instead. Generally speaking, the important thing to be remembered about all large schemes for dealing with the sea is precisely that they are not only beyond our technological capabilities but also beyond any prediction of their ecological consequences. There are, however, still other reasons why they will not be tried for a long time to come.

One of these is a political matter—namely, that the extraterritorial waters of nations near their shores are international territory. The creatures in it were *res nullius* (nobody's property) even before the days of ancient Rome. Traditionally, they have belonged to whoever took them into his possession, to deal with as he saw fit, and in theory were resources to be shared by all. For some of those resources there is fierce competition, whereas others remain untouched and still others are exploited by a single nation. Before there can be any agreement over who is to be allowed to control and manipulate the products of which portions of the seas, the old concepts of conservation and the old laws governing living marine resources must be changed. The next chapter will be an examination of those laws and of certain impending changes to make them a usable basis for future conservation practices. For, if there is ever to be a gain in the potential harvest of the sea, conservation will be no less important than mariculture in bringing it about.

5

Saving the Harvest

Fishing Regulations

Any fisherman in the Western world who sets out for a favorite trout stream can expect his sport to be hedged by restrictions on the number and size of fish he may take and upon the season when he is permitted to fish at all. He can also expect to pay in some way for his right to fish, usually to a public or private agency for the conservation of a delicate and vulnerable resource. Few sport fishermen question the necessity for these restrictions, and thus there is little difficulty in enforcing them. But for the fish and other animals, such as whales, that inhabit the high seas the situation is different. The waters are international territory; they are not the property of a state, a club, or a landlord, and thus are the property of no one until they are captured. There are no international wardens; no fine is to be imposed for taking fish of sublegal size or in excessive numbers; no poachers are put in jail.

Such regulations as do exist are really no more than voluntary agreements and conventions, which state, first, how nations might go about cooperating on the high seas and then what might be done in a particular instance, to save a resource that is threatened by overexploitation. Often such conventions embody the concept of sustained yield, a concept that was only recently applied to the sea. It is simply the idea that stocks of marine animals are to be studied and the take adjusted so as to

allow for approximately the same harvest from year to year. Except in the event of external catastrophe—such as a change in climate, an epidemic, or widespread pollution—sustained yields can be maintained if proper care is exercised. Foresters have followed the same principle for many years. Fishermen have not done so because the animals they took and the waters from which they were taken were under the care of no one in particular, and it was in no one's direct and immediate interest to take responsibility for their management. Everybody who took part in the exploitation merely was afraid the other might have taken more than he did—with the result that there was a cutting off of noses to spite more than one face.

Some economists have argued that management for a maximum sustained yield may not be in the best interest of nations dependent on the fishing industry; that is, if the proteins are very badly needed, either for use as food or as an item of trade, a nation may rightly take the cash and let the credit go. The intensive whaling practiced by the Japanese is an example. Since whale meat is eaten by few other nations, whereas the Japanese consume it in quantity, some of their tuna catch is available for export—and must be exported if the nation is to avoid economic ruin. For other nations, a longer view into the future and a willingness to abide by the concept of a sustained or steady yield may be possible.

Whaling

There are those who point out that there have always been Jeremiahs and that substitutes for vanishing resources have often been found in the past. This view, especially when it concerns plants or animals that reproduce freely, is the product of a frontier philosophy, prevalent when there were what appeared to be endless stretches of virgin territory. Now there is no more such territory, not even in the Antarctic, where a

clear-cut example of the difficulties of regulating a common resource on the high seas is that of the blue whale. Whales are mammals, not fish, but since they also eat plankton or smaller fish, they are subject in every way to the ecological principles governing the numbers of marine animals. The fate of the largest of all the species of whales is a case history of perhaps inevitable but nonetheless deplorable mismanagement.

Technology has affected many kinds of fishing, but the hunt for the whale has become the most highly mechanized of them all. In the early days of whaling the contest between man and whale gave the giant mammal something like a fair chance of escape, and the pursuit and killing of the whale required the utmost in courage and endurance from the men who engaged in it. Today whaling is thoroughly industrialized—the most successful, and the most destructive, exploitation of an animal resource by the human race. Seldom has a quarry been so relentlessly pursued as this, the largest animal that ever lived. A single good-sized blue whale is worth at least $5,000; its blubber, rendered into oil, is used in margarine, soap, and paints, as sizing in the rubber industry, and for many other purposes. The bone, and some other parts, yield meal and glue; the internal organs yield vitamins, hormones, and similar products for the drug industry. Some of the meat becomes animal food; much of it is also eaten, either fresh, frozen, pickled, or canned, and as meat extract, by human beings—notably in Japan, which is now the largest whaling nation. Some whale meat, mixed with fish paste, is made into a Spam-like product or a substitute for hamburger. Still another valuable whale product is ambergris, a waxy secretion from the intestine of the sperm whale, where it accumulates around the indigestible remains of giant squid on which the species feeds. Since a male sperm whale may reach a length of 60 feet, and since it preys on even the largest squid, single clumps of ambergris weighing almost a ton may be retrieved. At times, also, the whale voids a

mass of ambergris, which is then washed up on the shore. In ancient times the substance was reputed to have aphrodisiac qualities and was eaten as a cure for hysteria. Later its use was limited to the perfume industry, where it was valued both for its own musk-like odor and because of its ability to bind other aromatic substances—so that possibly it is now a more effective aphrodisiac than in the past.

The whales, an order of large mammals that returned to the water from the land, where their ancestors had come to be at home, range in size from the 4- or 5-foot dolphin to the 100-foot blue whale. They are, of course, warm-blooded and give birth to live young. A healthy blue whale calf measures 25 feet at birth and gains nearly ten pounds an hour as it feeds intermittently on the oily, yellowish-white, pungently flavored milk offered by the mother as she rolls sideways, extruding her otherwise infolded pair of dugs. The whales that are of interest to man as a hunter are mainly the large ones, which fall into two groups with rather different habits. The first group includes the toothed whales, the porpoises of both fresh and salt water, the aptly named killer whale, and the sperm whales. They are all true predators. Some of them live on fish, some on squid. Still others, among them the killer whales, which hunt in packs, will attack anything that lives in the water. One male killer's stomach contained the remains of a dozen porpoises and as many seals. That they can be tamed like porpoises was shown by one that lived in a Seattle aquarium, but in nature they attack even blue whales, first eating the tongue of this large quarry while it is still alive. The toothed whale of commercial interest is the sperm whale, the species made famous by Melville's *Moby Dick*. Its huge squarish head comprises about a third of the total length and the lower jaw of its enormous snout contains teeth that may weigh up to four pounds each. A special cavity or receptacle in the head contains much oil, mixed with wax or spermaceti, both of which

lend buoyancy to the animal in rising from its deep foraging dives which may take it to a depth of 3,000 feet or more. In contrast to most of the other whales that are now hunted, from which it differs mainly in its food habits, the sperm whale frequents tropical rather than polar waters. The species is polygamous, twelve or fifteen females making up the harem of one large male. In old age the male loses his harem, becomes fierce and solitary, and may stray into the northern or southern polar seas.

The second large group of living whales (those of a third group are known only as fossils) are the whalebone whales or *Mystaceti* (from the Greek words *mystakos*, meaning mustache, and *ketos*, meaning whale). In embryo they have vestigial teeth, but in the adult these are replaced by a series of 300 or 400 flexible, horny baleen plates (the so-called whalebone) arranged vertically along the upper jaw, each with a brush-like lower border; in the Greenland whale a single plate may measure 15 feet from top to bottom. The tongue rises behind the plates and has a central groove leading into the gullet. Blue whales and their relatives swim through polar seas where plankton crustacea abound, or through shoals of small fish, with their mouths open. The food is strained by the fringes of the baleen plates and gathered along the tongue, while the mouth is intermittently closed. The food-gathering mechanism is extraordinarily efficient; the stomach of a large blue whale may contain up to two tons of thumb-sized euphausiid shrimp, which is its main food, and which is most densely concentrated in Antarctic surface waters.

Accounts of whaling in the northern seas go back to the time of King Alfred, in the ninth century. By the thirteenth century, it was an important industry among the Basques. By 1550 the English and the Dutch had set up shore stations on Spitsbergen for rendering whale blubber and were pursuing whales with 200-ton sailing vessels that carried several pinnaces, light vessels each rowed by 48 oarsmen. Whaling stations were the

forerunners of later Antarctic shore factories, and had such amenities as spirit depots, bakeries, inns, and churches. American whaling developed during the seventeenth and eighteenth centuries and had reached its heyday by 1850, when a fleet of over 700 sailing vessels pursued the three main species of whales over all the world's oceans.

The species hunted by the Basques and the Dutch, known as the Basque "right" whale and the Greenland "right" whale, respectively, are shorter and sturdier creatures than the blue whale and, unlike most other species, they remain afloat after being killed, hence the word "right"—right for hunting, that is. Right whales are also supposedly slower and more peaceable than the others. The carcasses either were towed to shore stations or, as whalers ventured farther out to sea, were lashed to the side of the ship, so that the blubber could be peeled and rendered into oil in a brick furnace aboard the ship. At times the furnace was stoked with the refuse of the whale itself; the stench and gore aboard a whaling ship out of Nantucket or New Bedford must have been distinctive.

In place of right whales, early in the eighteenth century, the Massachusetts whalers began to hunt sperm whales. They not only also floated after being killed but yielded, in addition to the oil from the blubber, the highly prized oil from the cavity in the head, along with spermaceti, which was used for making candles and pomades, and an occasional clump of ambergris. However, only baleen whales yielded whalebone, which was used in making stays for ladies' undergarments. The most important product of all, though, was the oil, which was burned in lamps until petroleum began to take its place. The right and sperm whales were relentlessly hunted, and their numbers became fewer and fewer. As a consequence, traditional methods of whaling declined because it had become a poor risk for capital investment.

The whalers of the nineteenth century had seen blue whales and their somewhat smaller cousins, the fin whale and the

rorqual, of which the latter sometimes occurred in north temperate seas. These whales were too fast to be pursued by sail and oar; the hunt for them came with the harnessing of steam and then of diesel power, and the invention of the explosive harpoon, patented by a Norwegian, Svend Foyn, in 1870. Since then it has been modified only slightly, and has been used to kill many hundreds of thousands of whales.

In the Southern Hemisphere, whaling stations were first operated around the turn of the century and pelagic whaling from factory ships was first tried in 1923. It skyrocketed during the years between the two wars and has been going strong ever since, though by now it may be near collapse. A factory ship such as the *Sovjetskaya Russia,* built for the U.S.S.R., displaces up to 44,000 tons and is equipped with a movie theater, hospital, and library, as well as with devilishly efficient machinery for disposing of the carcass of any whale that is pulled aboard over the inclined slipway at the stern. Within half an hour a 50-foot leviathan can be made to vanish from the deck and into the open maws of pressure cookers, meat grinders, freezers, and so on. Attached to the mother ship are a flotilla of catchers between 100 and 150 feet long, high-bowed, fast, and seaworthy, and stripped down for action. The harpoon is mounted on the bow platform, and is reached from the bridge by a gangway that is almost always slippery and often covered with ice. From the platform the master gunner aims the barbed shaft with its explosive head at the whale's body from a distance of about 50 yards. Great skill is needed to gauge the whale's undulating path as it rises to the surface to breathe and to guide the vessel within shooting distance. Blue whales, finbacks, and rorquals, all species that sink soon after death, are heaved to with the catcher's powerful winch, inflated with compressed air, studded with a radio buoy, and cast adrift to be picked up later—by the catcher, by a pickup vessel, or by the mother ship itself.

A harpooned whale dies slowly; the vapor from its final gasps turns pink and then red with blood, while the horizontal flukes of the great tail thrash a vermilion sea. Once the men could be swept out of a pinnace by the beating tail, but nowadays the hazard of whaling is mainly in missing the whale. An animal that has been harpooned once or twice, with a weapon that acts like a load of shrapnel inside the body, has little chance of survival. Apart from avoiding unnecessary cruelty, there are other reasons for wanting to improve on the weapon and to shorten the struggle. One is that the more exhausted the whale the poorer the quality of the meat as a result of poisons accumulated in it. Another, though less frequent, problem is that if fragments of the harpoon are scattered through the animal's body, the cutting tools may be damaged. In recent years whaling companies have been experimenting with electric harpoons; a conductor has been developed that stretches at the same rate as the nylon line of the harpoon itself, and the proper current and rate of impulse to kill a large whale almost at impact have been discovered. The meat of animals harpooned in this way is far superior to that of whales taken by the explosive harpoon; also, the whole process takes far less time. Provided the whales have not been exterminated in the meantime, the electric harpoon is likely to replace Svend Foyn's explosive device just as it in turn replaced the hand-thrown spear of Melville's day.

Overfishing

This section might more correctly be called "overwhaling." At any rate, whales are resources of the high seas that belong to no one, just as the fish are. The decline that is the result of their heavy exploitation is symptomatic of the fate that has befallen or appears about to befall other aquatic animals. The first to go were the right whales and after them the sperm

whales, whose pursuit ceased to be worth the financial risks involved. Fortunately, this exploitation of marine animals has not led to their complete extinction, since a man who fishes for profit usually begins to look for other grounds or another quarry long before he has taken the last of a species. The part played successively by several kinds of whales in modern whaling bears this out.

Antarctic whaling began with the blue whale, the largest and perhaps also the most prevalent species, which continued as a mainstay of the industry until about 1937. With the resumption of whaling after World War II the take of blue whales declined from nearly 8,000 in 1948 to less than 2,000 in 1955; in 1962 only 1,255 blue whales were shot. At the same time the somewhat smaller finbacks were taken with greater frequency, the total having risen from just over 20,000 to more than 30,000 animals per year, but their numbers are now also declining. The sperm whales have slowly recovered from the decimation inflicted by the Yankee whalers during the nineteenth century, and the numbers taken rose from about 9,000 in 1948 to more than 23,000 in 1962.

It is not only numbers or tons that count, however, but also the effort expended in securing the whales. As has already been emphasized, the ultimate quantity of protein that any region of the sea can offer is finite and may even be appallingly limited. Among a newly exploited stock there are at first many old individuals, which are usually taken in preference to younger ones because they are the largest. As they disappear, the younger animals that remain have access to more food, grow faster, and thus may even mature earlier; also more of the young may survive. As the fishing goes on, and immature animals are taken, the reproductive potential of the stock diminishes and the yield declines. But there remains the heavy investment in the tools of capture and in related industries, which the man doing the exploitation is not ready to give up. Often, on the contrary, the effort at exploitation is redoubled,

and so it has been in whaling and in many other fisheries. In Japan, for instance, the food-processing industries have put so much money into whaling that a complete cessation of the hunt would have economic repercussions far beyond those industries themselves, since the mother ships, catchers, and factories for processing whale meat and oil are far from being amortized.

Now that there are no more unexploited stocks of whales, the fishery has had to be regulated by international agreement if there are to be any whales left to catch. In 1946 an International Whaling Convention among the nations that hunted the whale was called by the United States. Yearly quotas were proposed for the various species; there were agreements on protected grounds and closed seasons. It was also agreed that inspectors representing an International Whaling Commission were to be carried aboard all factory ships and on shore stations, to carry on a sort of internal policing in the absence of any supernational enforcing power for limiting the take of a resource that belongs to no one. International agreements are hard enough to reach between two parties; the problem is compounded when there are as many as thirteen participants, as there were in the Whaling Convention. The three hardest to convince were the U.S.S.R.—since the great increase in her whaling potential meant that the greater the cutback forced upon her the greater the economic losses; Japan—which has an urgent need for the fats and proteins she takes from the sea; and Norway—which had been the world's chief whaling power for many years as a result of Svend Foyn's invention of the explosive harpoon. Also, Norway supplied gunners, cutters, flensers, and other skilled workmen to the industry, as well as having made heavy investments in whaling fleets. In fact, during the Whaling Commission's first decade it was hoped that Norway's pre-eminent position in whaling, and above all her virtual monopoly on the supply of gunners, might somehow exercise a limitation upon the take. But members of other

nations, assisted by electronics and other advances in guiding ships and harpoons, also learned to shoot whales. Soon there were gunners of several nationalities, including many Japanese, and whale hunting became more and more intensive. As the animals became scarcer, some of the products derived from them went up in price, thus compensating for the shortage.

In 1964 the Commission recommended a limitation of the take to 4,000 blue whale units, a drastic reduction from the 1953 quota of 16,000. A blue whale unit, the basis of present Antarctic whaling regulations, makes one blue equivalent to two finbacks and to six other baleen whales. Thus what is regulated is not the number of individual species but the total take, with allowance supposedly made for differences in abundance. Norway, Russia, and Japan countered by insisting on a limit of 8,000 units instead of the recommended 4,000. But, in spite of the most intensive fishing, none of the three could reach this quota. Early in 1965, after Japan had purchased what remained of the Dutch whaling fleet in an effort to increase her own percentage, the Commission again proposed a limit of 4,000 units; 4,500 was the number finally agreed upon for 1965–66.

Once a quota has been agreed on, the Commission works smoothly. Long before the days of the United Nations, one nation was allowing inspectors and scientists from another aboard its mother ships to check on numbers, sizes, percentages of immature whales in the catch, and aspects of whale biology. The percentage of immature whales in the catch, incidentally, is a good indicator of fishing intensity; the more there are the closer is the point of overfishing and of diminishing returns, if it has not already been reached. In the Antarctic catches the numbers of immature whales have been increasing steadily for many years, and it was evident that the population could not be maintained at the rate of exploitation that had been imposed on them.

Continual radio contacts between the inspectors on the mother ships, and running tallies during each season, led to a cessation of the hunt when the quotas were reached. These quotas, however, were so much in excess of what would have been dictated by sound conservation that it was not the quotas themselves but rather the Antarctic winter and its accompanying violent storms that halted the intensive hunting. The old proverb concerning a "bird in the hand"—which in this case meant many millions of dollars—was applied too literally to this living resource of the Antarctic seas, and if it continues to be applied, there will very likely soon be no more "birds in the bush," so far as blue whales are concerned.

In fact, it may already be too late to save the blue whale. In 1962 the lowest estimates of biologists placed its numbers at between 900 and 3,000—a figure that in 1963 declined to between 650 and 2,000. The last remaining members of the species will probably not be taken by man, but even if they are not exterminated with harpoons, there may be too few to reproduce efficiently. We do not know enough about their biology to say definitely what the effective minimum might be, but judging from what is known of other species of large mammals it appears unlikely that blue whales can persist when there are less than a few hundred, or perhaps even a thousand, individuals. It would indeed be to man's discredit to have exterminated the largest animal that ever lived on earth at a time when the consequences of his relentless hunt could already have been foreseen.

The Fur Seal

Some biologists, pointing to the fur seal as an example of a species of marine mammal saved from extinction in the nick of time, regard it as a hopeful sign that the hard-pressed Antarc-

tic whales will recover when it has become no longer economical for the floating factories to make the long voyage necessary for their capture. But the biology of the seal is so different from that of the whale that only the roughest analogies are possible.

Two species of the eared, or fur, seal, first cousins of the sea lion and second cousins of the true seals and walruses, are known, one occurring in southern and the other in northern polar seas. The southern species was hunted first; beginning in 1784, millions were taken during a scant fifteen years. By 1800 they had become extinct on that archipelago. One after another, new seal rookeries were discovered in the Southern Hemisphere, and the animals were slaughtered by the crews of European and American vessels. The skins were largely destined for China, where they were made into fur caps and collars, and used for trimmings on the robes of officials. Now only two sizable populations of fur seals remain south of the equator—one living at the tip of South Africa and the other on the Lobos Islands, off Uruguay; in both places they are protected and harvested selectively, so as to maintain a good breeding stock.

The seals of the Pribilof Islands in the North Pacific were discovered in 1786 by the Russian navigator Gerassim Pribilof. From old accounts it may be estimated that the herd once numbered more than five million. About two million hides were processed in the fifty years following the discovery of the islands. Then the Russian managers grew apprehensive of a decline in the numbers of seals and began to impose restrictions on the number killed. The seals' natural history is such that conservation measures are easy to apply while still permitting a steady take of surplus animals.

Males and females both live about fifteen years. The females begin to breed when they are two years old and give birth to their first pups at the age of three. Males do not mature until they are six or seven years old. In the spring, after a winter at

sea, they arrive on the islands, and the mature bulls, which form the advance guard, select a beach area which they defend with threatening, bellowing, and posturing but little real fighting, while the older and more experienced bulls stake out the best territories. When the cows arrive early in June, each bull acquires a harem of between fifty and a hundred females. The pups are born soon after the mother arrives, and breeding takes place shortly after that.

The cows and pups are first to leave, usually in November; the males depart somewhat later. Among polygamous animals like the seals there are many surplus males. As they reach the age of three years they form bachelor societies that live away from the breeding part of the herd. The best seal fur is that of the three-year-old males, which can be segregated with ease and killed after a sufficient number have been spared to replenish the future breeding stock.

The purchase of Alaska made the Pribilof Islands an American possession. United States shore sealing operations were regulated, and for a while the herd continued to flourish, with many millions of dollars flowing into the Treasury from the proceeds of the private companies who leased the sealing privileges. The Indians, as they passed to and from the breeding grounds in their canoes, had speared fur seals in the open sea. But, whereas their harvest amounted to hardly more than a few thousand animals, at the end of the eighteenth century, when schooners carrying hunters from the United States and Canada, together with sailing canoes, began to take seals in the open sea, the animals no longer had a chance. On land the seal herd can be harvested selectively and a breeding population maintained, but if they are shot in the sea, there is no way of picking out the surplus males or exempting females and pups. Furthermore, since the females are pregnant while at sea, each cow killed also means that one less pup will be born. Many seals were injured and escaped only to die, and many of those

that had been killed could not be reached because of storms and fog.

Pelagic sealing obviously was an unwise use of a marine resource. But even if beneficial regulations of some kind could have been devised, they could not have been applied, since the harvest took place outside the jurisdiction of the United States, which controlled the shore operations—or of any country, for that matter. Seals in the open sea were common property. By 1910, after some seizures of vessels by the United States, and arbitration by a specially constituted tribunal in Paris, the herd that had once numbered 5 million seals had shrunk to 130,000, and sealing on the high seas as well as on shore had become unprofitable.

The time was ripe for concerted action by the nations involved to regulate sealing in the North Pacific, not only in the Pribilofs but also along the Asian shores. The United States, Great Britain (representing Canada), Japan, and Russia made a treaty agreeing to refrain from pelagic sealing north of the thirtieth parallel, each country managing its shore harvest as it saw fit while still permitting Indians and Eskimos to take seals at sea for food. In 1942 the treaty was replaced by a new but fundamentally similar agreement between the United States and Canada, covering the Pribilof seals only. An American fur company is entrusted with the harvest, and the United States gives some furs to Canada and Japan.

The conservation principle applied here—to entrust the management of a stock of animals exploited by several nations to one of those nations—was easily applied to the seals once it had become clear that pelagic sealing was too destructive. The animals bred on only a few islands belonging to the United States. For the fur seals this "sole management method" turned out to be highly successful; by 1950 the once nearly extinct herd had again increased to more than four million animals. But the fur seal, because of its way of life, presents a special

case, and unfortunately, as has been said before, the conservation methods applied to the seal cannot be applied to the whale.

Territorial Waters

Fish make up a far larger part of the marine harvest than mammals, but principles of economics as well as of ecology apply equally to both groups. For example, when several countries agree to manage some animal stocks jointly, as happened with the whales, there must be an agreement, among others, on the relative value that is placed on adherence to the restrictions as opposed to the prospect of obtaining a large return for a short period of time, and after that none at all. In some regions the quest for the sea's bounty is now so intensive that there are traffic problems in addition to that of conservation. For example, in 1962 French herring fishermen ceased operations off their own shores outside the territorial limits in protest against hazardous conditions for navigation caused by the large number of foreign vessels.

The management of certain fish stocks by several nations may become difficult for reasons of biology as well. Pacific salmon, for instance, breed in Asian and North American rivers but feed in the North Pacific, where in at least some areas schools from both continents are present together. The Americans fish for salmon only in their home waters, to which the fish return to spawn, whereas the Japanese fish both in their own estuaries and on the high seas. Conflicts arise because salmon caught on the high seas cannot return to spawn or else be caught near their home shores, and it is difficult to tell whether those caught are of Asiatic or American origin. Agreement on the subject can be reached only after much research and good will between the nations involved.

Inshore resources, such as salmon homing to spawn, would seem more easily manageable, since territorial waters are under the jurisdiction of the coastal state. Yet there are difficulties here also, some of them arising between nations. Formerly most nations agreed to a territorial limit of three miles, a distance supposedly corresponding to the range of ancient cannon placed in the forts on shore. Today territorial limits have lost their meaning for warfare, and mainly serve to protect a nation's inshore fish resources. Because the depth and character of waters near shore vary, as do the habits and distribution of fish inhabiting them in different parts of the globe, there is no universal agreement on the extent of territorial waters.

In 1958, at the Geneva Convention of the United Nations on the Law of the Sea, each of the eighty-six states represented stated what it considered territorial waters to be for the purposes of fisheries management. The stated width of such waters ranged all the way from 3 miles (twenty-one nations) to 12 miles (eleven nations) with some claiming 5-, others 9-, and still others 10-mile limits. Still others claimed the waters above their continental shelves, however far out the latter might extend, and still others, including Peru and other states along the western coast of South America, which have no shelf but are characterized by upwelling waters offshore, claimed a width of 200 miles. Since 1958 a majority of these nations either have agreed or are ready to agree on a 12-mile territorial limit.*

Some international fishing agreements can be reached more speedily, though, especially if they are controlled by only two adjoining nations. The stocks of halibut in the Northwest Pacific were declining under heavy exploitation by United States and Canadian fishermen. More powerful boats, larger numbers of hooks, and more frequent voyages all resulted in

* The United States extended its exclusive fishery zone from three to twelve miles by Congressional Act in October, 1966.

fewer fish per boat and per man. Clearly the halibut were being fished too heavily to withstand the pressure. The two nations formed an International Halibut Commission, which entered on an intensive joint study and came up with a quota system that limited catching units. The marginal operators left the industry, which now has not only recovered but has even exceeded the total yearly take before the agreement, and is operating on the basis of a sustained yield.

The International Halibut Commission worked so successfully because Canada and the United States are friendly and have roughly the same economic interests, at least in the coastal Pacific regions involved. Also because halibut move about less than many other fish. Of course, operating with fewer and more efficient boats than before, and for a shorter season, as a result of the Commission's regulations, poses some problems to fishermen. They make a reasonably good living from their profession, but if they were to fish only for halibut, their tools would lie idle for much of the year. This state of affairs is good neither for boats nor for men, and consequently they try to catch other fish. Some, especially temporary crew members, may also go lumbering.

Halibut fishing on North America's west coast is done in near-territorial or what are known as contiguous waters. Any nation has the right to engage in the fishery there along with the United States and Canada. Japan, the most likely candidate because of her interest in the North Pacific generally, agreed to abstain from halibut fishing off those coasts. Yet we have no prescription and certainly no law to guide us if Japan or another nation were to decide one day that the halibut on the Pacific coast were also for them.

Some disputes have already arisen over animals in contiguous or continental shelf waters. Many nations have now ratified several of the conventions passed at the 1958 United Nations Conference on the Law of the Sea. One of the conventions has

to do with the sea bed and subsoil resources of the continental shelf. The regulations on exploiting the latter, of course, have an important application to the tapping of petroleum and other mineral riches in and below the sediments; those regulations will be discussed in the next chapter. But living resources of the sea bed belong to the realm of fisheries, where they can pose some knotty problems.

The Truman Proclamation of 1945 established control by the United States over the "natural resources of subsoil and sea bed of the continental shelf beneath the high seas but contiguous to the coasts." In essence, the ideas of the proclamation have been incorporated into the Geneva Convention mentioned above and have been ratified by many nations. The shelf is taken to extend to a depth of 200 meters and also beyond, where the state is capable of exploiting whatever natural resources are present. These resources were defined as minerals and sedentary species, which "at the harvestable stage are either immobile on or under the sea bed or are unable to move except in constant physical contact with the sea bed or the subsoil."

Some kinds of animals on the shelf, such as pearl oysters, which are permanently attached, and sea cucumbers, which crawl about, clearly fall under the control of the shore state, but concerning others such as lobsters there have been differences of interpretation. When spiny lobsters from the continental shelf off Brazil were taken from certain efficient and technologically advanced French fishing vessels, the Brazilians protested and threatened to attack with gunboats, asserting that the animals were on the sea bed of the Brazilian continental shelf and were therefore Brazilian property. The French, however, replied that they would protect their fishing boats with their own warships and that the Brazilians were clearly wrong; that the lobsters were a free resource since they occasionally rose from the sea bed, flapped their tails, and changed their abode. The Brazilians were duly advised that the French

were right at least biologically. Some legal experts jokingly suggested a compromise, namely, that the Brazilians be permitted to catch the lobsters and the French to cook them; then everyone would be satisfied.

Tasks for Future Lawmakers

This chapter should have demonstrated that new concepts of the regulation and management of ocean resources must be sought if we are to be successful in the stepped-up exploitation of our last frontier. One of the questions that must be answered before these concepts can be formulated concerns the high seas: Should they be thought of in terms of species or of regions? Whales and tuna, roaming far and wide, large in size and of high economic value for each unit caught, are "regulated" as a species. Tuna biologists recognize, however, that they must also deal with the food of the tuna, which is regionally restricted, wherever the tuna itself may be. With the anchovies off South America or the menhaden off the east coast of North America, regional considerations are important; for halibut and lobster, it is necessary to consider both the species and the region.

No set answer can be given, except perhaps to quote from Francis Christy and Anthony Scott's *The Common Wealth in Ocean Fisheries:* "The world has not yet sufficient scientific knowledge to predict accurately the consequences of even small changes in the use of most parts of the oceans." But obviously we cannot wait for the acquisition of this knowledge before formulating conservation and management principles or regulations.

Another question concerns the best way to organize the fishing effort. At present, regional councils under UN auspices reach voluntary agreements here and there. But for the future, one must examine still other possibilities: Should the oceans be

carved up, giving each of the shore states certain extensive grounds? Further, to what extent can or should historic rights and needs, as, for instance, those of Japan, be recognized? Might an alternative be to extend the principle applied by the fur seal treaty to much larger areas and tonnages? There would then be recognition of the rights of nations to the benefit of the fishery that might be undertaken by an "agent nation" which in turn would distribute shares and keep a royalty, as it were, for its own efforts. Perhaps the most appealing solution from the point of view of both economics and conservation would be a truly international authority for harvesting and managing the living resources of the sea.

Christy and Scott point out that such a world fish authority could operate more cheaply than would be possible to most individual nations, since they could buy both labor and capital at the lowest prices and at the same time sell at least a part of the catch at the highest price. Considerations would be given to the common good and to protein needs satisfied through new techniques (for example, fish protein concentrate) from underharvested stock (such as hake). There would also be an opportunity to begin slowly and to phase out existing earlier agreements with a minimum of economic hardship. No one, in short, would be able to say, "If we don't get these fish, someone else will"—and there would no longer be unbridled competition for the ultimately limited living resources of the sea.

Whether or not such a utopian state is ever attained, there is yet another aspect of the sea that the world's nations must view, at first individually but eventually together. This is that changes in the environment induced by man have wiped out or restricted many plant and animal species on the land and in fresh waters. The passenger pigeon, for instance, was decimated while the beech forests that nourished the birds and provided them with nesting sites were being logged. The unique lemurs of Madagascar face extinction not only because

they are eaten by the natives but also because the virgin forest that shelters them is being carved into parcels too small to permit the lemurs to survive. The fish of lakes and streams are likewise more prone to suffer from man-made changes than are those that range far from the shore. Intensive cultivation on the land causes silting; removal of plant cover raises the temperature of the water; domestic wastes render it too rich for the comfort of many fish; and industrial effluents often poison it.

Near shore, in territorial waters, industrial and domestic effluents have played havoc with fish and oysters, as well as with bathing beaches. With the exception of a few atomic test sites, men have thus far made little impact in any way other than by hunting on the creatures of the high seas. But men will soon have the equipment to move underwater with ease and to live there if they so desire; they may live on the sea's surface, far from land, in settlements of considerable size; they may then pump up water from the depths to fertilize the surface; they may dig and scrape the ocean floor. We are clearly embarking on an era when the secondary effect of our activities other than fishing will be felt far out at sea. In the final chapter we shall examine the sea and man's future, aside from his quest for food. Meanwhile, it is well to bear in mind the hope that we may have learned a lesson from what we have done with the land as an indirect result of certain aspects of progress. One such hope is that the next convention of the Law of the Sea will include agreements on all aspects of marine pollution.

6

Horizons

Wastes and the Sea

So far we have looked at the sea mainly as a storehouse for food, with only a passing mention of how the ocean's capacity to produce has been affected by human activities. Among such activities is the dumping of discarded materials—notably domestic and industrial wastes.

The American people have been described as standing knee-deep in filth while shooting rockets at the moon. Despite the seeming paradox, it may be observed that rockets mean industry, and industry means waste products, as well as sites where people live crowded together. It might even be argued that pollution is justified on the grounds that our rocketry would not exist without it. But engineers and scientists, and politicians too, are now aware that most of the pollution in rivers, lakes, and the sea could have been prevented.

It happens that the early warnings implicit in sporadic fish and shellfish kills and in certain gradual changes in water plants and animals, due to the abuse of our waters, were all disregarded. Similarly, there was only brief alarm when nickel ions and cyanide wastes from isolated industries worked inevitable havoc with aquatic life; for in the past there had been plenty of water to undo the damage. Although we are now conscious of pollution, the effects of domestic wastes in particular are still easily disregarded in a nation only 5 percent of whose working population grow crops from the soil. The rest

cannot be expected to know or care that animal excreta—including those of human beings—make excellent fertilizer. Farmyard manure, once widely employed to enrich the soil, is hardly used any more, and whoever flushes a toilet in a town or city is simply relying on the municipal sewage treatment plant to take care of things.

Today even the best sewage treatment still leaves 10 percent or more of the organic material originally present in an undigested state, ready to enter the waters into which it is emptied. Many treatment plants don't work even that well, however, and some municipalities provide inadequate treatment or none at all. Agricultural runoff, which of late has brought with it a formidable load of insecticides, also finds its way to the rivers and finally, at least in part, to the sea. In 1963 the killing of large numbers of fish in the Mississippi delta illustrated clearly that a small poison-spill from upriver—waste from an insecticide plant happened to be the culprit—affects what goes on in its estuary and beyond.

We add staggering amounts of organic waste to the coastal waters every year on the careless assumption that these materials will be swept out to sea, there to disappear forever. How far from true this assumption is has been shown in St. Joseph's Bay, a Florida city with three industries and one municipal waste-water treatment plant. Phosphorus, probably the most important single nutrient for the growth of plants, was twenty times more concentrated in the bay waters than in the open gulf, with nitrogen next on the list. Consequently, a dense algal scum formed and was swept toward the beaches. It was the bathers who complained, but fishermen have raised their voices as well, because certain algae, especially those that grow under just such conditions, are poisonous or the smell causes fish to leave the area.

In the complex environment near the shore many plant and animal species are to be found, though not as many as in the open sea. In the presence of organic wastes—which is another

way of saying pollution—the number of such species declines, while the numbers of individuals goes up. St. Joseph's Bay had experienced just such changes, with the result that its waters now teemed with a few pollution-tolerant species of plankton. The reduction in food species—which, as we have seen, must be diverse in order to satisfy the needs of the fish at various stages of their life cycle—had led to a reduction in the kinds of fish.

The pollution of shore waters by man seems inevitable and is aggravated by the increasing pollution of rivers. Although the changes that occur in the wake of added organic wastes are slow, they can be measured over the decades in certain bays, lakes, and bayous. Along the open shore the comparison would have to be made over the centuries, but the changes are there, and they are inexorable. As we add outright poisons—such as oil, which kills waterfowl, or chemicals from industries—we make it difficult to use the edge of the sea for either our pleasures or our needs; San Francisco Bay is a good—or, if you will, a bad—example.

First to be affected are the sessile animals; many an oyster ground has been ruined and many a population of crabs has vanished as a result of toxic ions. In these situations, "delayed or indirect effects often turn out to be the most important feature uncovered by a given investigation [of toxicity]," according to the report of a seminar on biological problems in water pollution. The experts went on to warn against being satisfied if certain suspect waters did not kill the animals in exposure tests. The sublethal effects that may still occur will often prevent spawning, so that the population of fish or shellfish will disappear even though none have succumbed immediately.

More than 60 million people live within 50 miles of the coast of the United States, in a land area that represents less than 10 percent of the country's total. Already this coastal region

contains nearly a third of the population, whose increase has been faster than in most other regions. Such great increases have occurred not because of higher birth rates but rather because the vast industrial complex near the shore has afforded the best employment opportunities.

Each year hundreds of beaches are closed because untreated sewage has brought about a health hazard, disease-producing bacteria having become adapted to life in sea water. Metal poisoning from industrial wastes has killed shellfish and turned once fertile estuaries into biological deserts. At the same time recreational pressures on those same shores have increased—not only for the purposes of swimming and boating but also on the part of marine anglers, whose numbers are growing at a faster rate than are those of fishermen in lakes and streams.

The laws and practices concerning the use of water for waste disposal and for industry are antiquated and are just now beginning to change with the changing times. They date from an era when water was plentiful, a free benefit that did not have to be used over and over again as it does today. For instance, a law demanding that the water intake of all industries on a given river should be below their own respective outflow would reduce pollution almost automatically. However, such a law could never be passed because it would seriously curtail the rights of individuals and would impose unequal economic burdens—discriminating, for example, against new installations, since those in existence could not easily be changed. By whatever method, nevertheless, the control of water quality must become more rigid, and there must also be a realization that ocean bays and estuaries, the ultimate places of disposal for many pollutants, cannot be dealt with as though they were bottomless cesspools.

The dumping of wastes on the surface leaves visible effects (Fig. 49). These might be prevented by directing sewage pipes deeper and deeper into the sea and farther offshore. If such

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Fig. 49. Ducks dead from oil pollution.

deep dumping of sewage, but not of truly poisonous industrial wastes, were done with special spreaders (not yet invented), one might slowly increase the fertility of large ocean areas. Eventually, as such pipes were extended from time to time, they would reach a water layer distinct from those layers above it. Nutrient wastes and poisons might accumulate there, be diluted, and perhaps not reappear until millennia afterwards. Such a scheme is probably far too costly to be anything but a mental exercise for making political hay, and by reason of its size it has one major flaw, namely, that we don't know its long-term effects, and that these must be considered in view of the millions of years during which our planet may still have to remain inhabitable. Meanwhile there must be a realization that each man is responsible not only for his immediate environment but for the communal environment as well. Perhaps such ideas will take hold when communities are obliged to begin purifying river water for the express purpose of using it over and over.

On almost any river successive users of the same water will now be using it several times over; in fact, many will have done so for decades, while relying on dilution by sheer volume. Now

that the population has become denser, many a municipality is being obliged to consider immediate cleansing and re-use without dilution. Much research on the large-scale re-use of water is now in progress, with the aim of making quickly potable even the water that has just gone through the toilets. For instance, either instead of or in addition to a degree of conventional treatment, sewage might be passed through coal filter beds. In the first step of the process, which takes twenty minutes, a mixture of coal and the absorbed sewage is continuously removed, to provide an effluent superior to that made possible by any current primary sewage treatment. In the second step the effluent would be passed through another coal filter, in which further purification of the water would take place; it would come out as clean as the city water from most sewage plants that have secondary treatment relying on bacterial digestion of the organic material. The entire process would take from two to four hours, a fraction of the time required for conventional digestion and oxidation, and it would also cost less, in part because less land is required for the plant, in part because the coal could be used as fuel at close to 90 percent of its original combustive value.

A variant of the two-step coal process would use finely powdered diatomaceous earth to remove the suspended solids and would then rely on activated carbon (highly porous charcoal) to absorb the remaining organic compounds—including those phosphates, detergents, and insecticides that pass unaffected through a conventional plant. If the water was brackish or if it contained minerals from industrial wastes that were not absorbed in the coal process—which is mainly geared to deal with the organic materials—electrodialysis, powered electrically by burning coal from the filter beds, could be employed to remove these salts. The water could then be re-used with little loss and would meet all standards of purity. In fact, it would be possible to combine either electrodialysis or coal filtering with conventional treatment methods. Such combina-

tions are likely to be employed. Indeed many new sewage plants based on the coal-filtering method are now under construction or on the drawing board. But one needs to remember also that such conversions are expensive and that many presently inadequate plants will not be changed, for financial reasons.

Eventually, provided somebody is willing to pay for it, the Hudson and Delaware rivers may both be cleaned up, as well as the evil-smelling estuaries of such industrial nations as Japan and Great Britain. River water will still be used by the coastal megalopolis of the future, but the supply will come to it in a purer state, even after having been re-used many times over, than it now is. Depending on the degree of access to low-salinity brackish water, as it is found near Washington, D.C., or in parts of San Francisco Bay, there may well also be atomic-powered desalinization plants designed perhaps only to relieve the pressure in times of drought.

Research is needed to deal with inshore oceanographic problems related to waste disposal, and so is a probe into ways of resolving conflicts over the use of coastal waters. Since the resource in question is common property, the conflicts that arise are matters of public policy, and therefore the research will have to be supported by public funds. The Committee on Oceanography of the National Academy of Sciences and the National Research Council has estimated that the financial benefits from inshore oceanographic research, which is mainly connected with waste disposal, will be two or three times the amount of the money spent—and they are advocating a yearly expenditure of between $15 million and $20 million.

The pressing nature of this type of research is being recognized by the Federal Government; President Johnson, in his report to Congress on Marine Science Affairs, in February, 1967, mentioned that the new Council on Marine Resources and Engineering Development (to be mentioned in more detail later) considered the pollution of bays and estuaries and the

Great Lakes to require special attention. It is a hopeful development in this regard that the U.S. Army Corps of Engineers has been authorized to construct a model of Chesapeake Bay on a 1:2,000 scale, intended for interdisciplinary studies of the complex phenomena which influence this area. Of particular interest, the report says, "will be the understanding of the capacity of the Potomac estuary and subestuaries to absorb pollutants by using such a model at costs which should be relatively low compared to that of large scale field tests."

The pollution of beaches could be ended, oyster beds could be made to thrive again, and sport fishermen could still catch more bluefish, sea trout, and striped bass than at present. Whether this is to be the future of our shores or whether more and more of them will be lifeless, foul-smelling, and clogged with black slime depends on the foresight of the people who live along a nation's rivers and near its shores.

In addition to the fate of beaches near large cities there are other reminders that the sea is being fouled as a result of human thoughtlessness. Those reminders extend far beyond the shores to places where one would not expect them. An example is reported by Captain Cousteau from one of his first deep dives to the bottom of the Mediterranean. As his bathyscaphe gently settled on the sea floor he turned on the searchlight, illuminating a small segment of the abyssal realm. There he saw a large white object that seemed alive, and which he took for an unknown species of ray, gently moving its winglike fins as it prepared to swim off, disturbed by the intrusion of man. As he looked more closely, anticipating a biological discovery, the object turned out to be the front page of the French newspaper *Le Figaro*.

One of the most intensively traveled shipping lanes is the one leading to the Orient through the Red Sea, a body of water richer in marine life than most other seas.* In it there are islands

* It is "out of commission" at the time of this writing, however.

whose shores were once of unequaled beauty—white coral sands alternating with rocky coves dropping steeply into deep-blue waters. Today those same shores are littered with spent light bulbs and other trash and the sand is spotted with tar, the waste of freighters and passenger liners bound for Africa and the Far East.

With more and more oil being shipped every year across the world's oceans, it was likely that an oil-spill disaster due to shipwreck would occur one day. One hopes that the grounding of the *Torrey Canyon* off Lands End, in April, 1967, will have satisfied the statistical predictions for a long time to come. But even without shipwrecks, about a million waterfowl of various species die a lingering death every year as a result of oil pollution along the littoral of the Northern Hemisphere. The number is small in proportion to the total of all water birds, but a whole species can nevertheless be seriously affected when a flock encounters an oil slick. The razor-billed auk of Newfound-

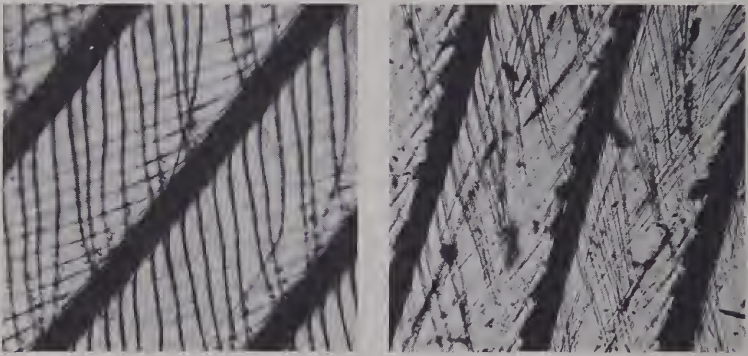

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Fig. 50. Photomicrographs of small portions of a duck's feather. *Left:* normal plumage capable of forming an insulating layer. *Right:* oil-soaked and matted plumage which lets water through to skin.

land is one such species. Water birds normally retain their body heat thanks to an insulated air cushion under the feathers. Water cannot penetrate to the body, mainly because the feather barbules form a dense regular mesh that keeps the water out by its own surface tension. When wetted with oil the barbules become matted, with the result that cold water reaches the skin and the birds finally freeze to death (Fig. 50). Sensing that something has gone wrong with their plumage, they groom themselves frantically, taking in oil as they do so. Those that recover from the loss of insulation, as some do, may still suffer internal damage from the oil. Furthermore, if there is oil on their plumage while they incubate their eggs, the tiny pores in the shell may become clogged, suffocating the young bird inside.

Oil slicks are particularly severe near important coastal shipping lanes, such as the North Sea and the east and west coasts of North America. But I have also seen once idyllic beaches in the Gulf of Siam that had been ruined by oil and tar. Within a few years the building of roads and harbor in Cambodia's new port had caused tar deposits to form on the shore. Black spots would adhere to the soles of one's feet from the once glistening, immaculate strip of white sandy beach. Palms still shade it, but under them the once blue waves are now laden with oil.

There are international agreements and local laws about voiding oil from ships, but these are only as good as the means of enforcing them. According to the report of a seminar on Biological Problems in Water Pollution, held in 1962, "Even if there were strict enforcement and observance of such regulations as exist, it is unlikely that complete cessation of oil pollution will result because of shipping accidents, oil line or installation defects and other human error and equipment failures. Enactment and enforcement of stricter laws by state and local governments are especially important since a 1960

survey showed a lack of effective local laws to be a particularly weak link in the problem of oil pollution control."

The United States petroleum industry, incidentally, favors strict enforcement of laws and regulations to prevent oil pollution. In a letter to *Science* (August 11, 1967) Frank N. Ickard of the American Petroleum Institute points out that the tankers, while carrying the most oil, may not be the main culprits in the case; smaller vessels and especially pleasure craft are also potential offenders, and seepage from sunken vessels or even from undersea oil formations contributes importantly to the oil slicks on coastal waters.

Just as oil damage tends to be highly regional, so does that due to radioactive wastes, which are now universally dreaded. The first of these were from atomic explosions, which were restricted in time and place and also in the extent of damage to marine life. Lauren Donaldson of the Laboratory of Radiation Biology of the University of Washington, who for years has followed the fate of the biota at Bikini and Eniwetok, writes: "No mutations in plant or animal life were discovered but this does not necessarily mean that they have not occurred. In the competitive ecology of a coral atoll, a mutant probably would not survive."*

Nuclear tests on land and sea are ostensibly at an end. The questions of whether or not they will be resumed, and of the biological consequences of a nuclear holocaust, are beyond the scope of this book. But in any event peaceful use is being made of nuclear energy, and atomic weapons continue to be produced. Some of the resulting wastes are being discharged into the ocean. What, then, is their effect at present, and what will it be in the future, when more such wastes may be expected?

The external effects of radiation do not concern us here, since those effects are not produced by wastes disposed of at sea. What is more, the dumping of barrels containing low-level wastes embedded in concrete has been virtually discontinued;

* *Science* (London), April, 1967, p. 51.

there are now better and cheaper ways to deal with the problem, such as fractionating certain deep subterranean rock strata by underground explosions and then forcing in the wastes along with liquid concrete, which later hardens in the resulting cracks.

It is generally believed that if materials from research reactors were still placed in the sea on a small scale, a thousand fathoms would be a safe depth, with no risk of interchange with overlying waters, at least not while the low-level wastes still retain their radioactivity. Studies are currently being made of designated shallower areas along the continental shelf which may be selected for the disposal of wastes because of their favorable current patterns. Such disposal is not foolproof, however. Barrels containing radioactive wastes have occasionally been washed up on beaches. These mishaps—which, fortunately, led to no radiation damage—are an argument not against dumping in itself but for greater care and vigilance in the process.

The most important radioactive materials now being added to the sea are those contained in the cooling waters of various reactors or power plants. There are few such plants as yet, and so long as no accidents occur the effluents are kept well below critical radiation standards for drinking water. Reassuring as this statement sounds, and great as is the ocean's capacity for dilution, the present attention to immediate effects on human health copes with only part of the problem.

Standards of safety for drinking water concern the water itself and not the plants and animals that live in it. These take up minerals from their surroundings and concentrate them at many times the density of their occurrence in the water, making no distinction between normal elements and radioisotopes. An isotope of an element important to the life functions of an organism will generally have a short radioactive half-life, but it will still be accumulated in various organs.

One element that enters into almost all reactions within the

living cell is phosphorus, of which the radioactive isotope P_{32} has a half-life of two weeks. A recent study at Hanford, Washington, showed that the concentration of P_{32} in the flesh of Columbia River fish was several hundred times that in the surrounding water. That other isotopes, such as cobalt 58 and 60 and potassium 40, were clearly detectable in the fish but not easily measured in the water testifies once again to the animals' tendency to concentrate certain elements from their environment.

The concentration may proceed by selective absorption, usually through the gills—as metal ions are—or by way of the food chain. In the latter event the important elements are those with a long half-life such as strontium 90, which resembles calcium, and which like it is deposited in bones, scales, or shells where it may come to be many hundreds if not many thousands of times as prevalent as in the water.

There are two reasons for concern in the natural tendency of organisms to concentrate elements and compounds from their environments—including such chemicals as insecticides, some of which have now turned up in fish of the high seas as well as in Antarctic penguins. One reason is that the animals may be used by man. Suppose, for example, that stocks of menhaden, a coastal fish, were to accumulate strontium 90 by way of the food chain, from water that had been declared safe for other uses. Supposing further that these fish—bones, scales, and all, as is the practice—were converted into fish meal and fed to chickens as a result of an error in monitoring the fish catch for radiation. If and when the error was discovered, the chickens would have to be placed in concrete and packed in drums, to be disposed of beneath the thousand-fathom line at sea. No such contingency has arisen thus far, but it would be rash to say that it could never happen in the future.

The second reason for concern has to do with the populations of the animals themselves. No long-term genetic effects due to biological concentration of dangerous isotopes have yet

been clearly demonstrated, at least not on higher animals, although indications have been noted that fish and other aquatic creatures very near the outflow of atomic plants are so affected. Studies with water fleas, which have a short life span and therefore afford the opportunity to follow many generations within a short time, have shown unequivocally that long-term genetic damage can occur.

Radiation-induced genetic mutations of long-term importance are recessive and only slightly debilitating to the individual. In sea fish, for instance, there might be a somewhat reduced tolerance of changes in temperature or salinity. Eventually there would also be a weaker population and a reduction in offspring. To quote from a chapter entitled "Fission Products and Aquatic Organism" in *The Effects of Pollution on Living Material* by the British scientist W. B. Yapp, ". . . it is considered by some authorities that there will be a reduction in the resources of the aquatic environment in time, as a result of the effects of radiation from the large scale disposal of radioactive waste on the organisms which are the subject of fisheries or of their food." The Russian scientist, G. G. Polikarpov, who has written the most thorough work so far on the effects of radiation on organisms in all kinds of waters, even goes one step further than his British colleague. He says, "Although we are still in the early stages of investigations of the effects of radioactive substances on marine organisms, populations and biocoenoses (groups of organisms in a particular part of the ecosystem), we are already in a position to draw the important conclusion that *further radioactive contamination of sea-water is inadmissible*" (author's italics).

Fresh Water from Salt

Newsprint in the abyss, spent light bulbs on coral atolls, oil slicks that kill ducks, a few thousand curies of radioactivity added to the sea—all are minor if disagreeable aspects of

human dominance over nature. Mainly, as we have seen, the problem of the pollution of rivers and the sea resides in the disposal of more conventional domestic and industrial wastes. The cumulative effect of some of these products of man's efforts on earth are adding to the difficulty of using coastal waters for one of the benefits that will someday be demanded of them, namely, as a source of fresh water for human consumption.

Though the cry of "Water, water everywhere, nor any drop to drink" is no less true today for a shipwrecked sailor than it was in the time of Coleridge (notwithstanding sea rescue emergency packs that can produce a small amount of drinking water), the same neither is nor was true for an able ship at sea. Since 1600, or before, sailors have relied on small evaporators to turn sea water into fresh. Today large-scale desalinization of ocean water is much talked about as a way to relieve the water shortages that more and more frequently plague many areas of the globe.

Of several methods of turning salt into fresh water, each with its own peculiar advantages and disadvantages, all have certain requirements in common: an elaborate physical plant and therefore a large capital outlay, plus the continuous input of energy needed to separate the dissolved solids from the liquid. Beyond these requirements, three currently promising methods of desalinization are quite different. The one most commonly used relies on evaporation by heating, and a subsequent condensation of the vapor remaining after the salts have been extracted. A second method relies on separation of the salts by freezing, a process that takes place on a grand scale in polar icecaps and icebergs. In a third the mineral ions are induced electrically to pass through selectively permeable membranes that eliminate salt from the water.

The heat of the sun is free and in arid regions its energy has long been used to evaporate sea water from shallow pools in

order to make salt. Since usually these same regions also lack fresh water and receive much sunshine, could not the process be adapted to the production of fresh water? Pilot plants have been built for the purpose, in which shallow concrete pans with black bottoms and panes of glass or sheet plastic are arranged overhead like the roof of a tent. The water evaporates, forming drops on the panes and collecting in gutters at their base, whence it is conducted into cisterns. The evaporating surfaces must be large and there must be ample circulation of the air to allow for the continuous escape of heat. These installations are quickly rendered inefficient by dust, are vulnerable to strong winds, and especially to destruction by hail. Even in the favorable climates of North Africa, India, and our own Southwest, less than a gallon a day (between 2.5 and 4 liters) is the most that can be hoped for from one square meter (or about 10 square feet) of evaporative surface.

When it is remembered that the urban use of domestic water may amount to anywhere from 40 gallons per day per person, as it does in Japan and in parts of Western Europe, to as much as 200 gallons per day per person in some North American cities, it becomes clear that solar desalinization of sea water can hold little promise. Even if a second gutter were to be placed on the outside of the panes, so as to collect whatever rain happened to fall, many square miles of such installations would be required on land or water merely to assist in supplying water to a city of a million or more. Such installations are expensive on a small scale, and with increasing size the cost is multiplied. In addition, so as to bring the fresh water close to the place of its use, their location, whether on land or at sea, would necessarily be in an area of great value for such other purposes as building or shipping. Therefore, the only regions for which solar desalinization might supply fresh water would probably be those not by the sea, but surrounding special project sites, such as mines in highland desert areas that are endowed by nature with an underground supply of saline water.

By contrast to these solar water stills, evaporation installations that rely on heat exchange through metallic surfaces become cheaper to run with increasing size. Also, certain aids to efficiency are feasible—such as reducing the pressure during evaporation and increasing it during the condensing phase or enlarging the surface for heat exchanges by the use of a honeycomb design. In what is called the Multi Flash Evaporation Vapor Reheat Process, vapors are made to condense directly on the surface of a stream of cold fresh water, thus eliminating the energy-draining metallic surfaces.

By whatever ways engineering skill may yet be brought to bear on the process, the fact remains that the last hundred gallons of fresh water distilled from any given quantity of sea water will require for their extraction twice the energy needed to obtain the first hundred, simply because the basic brine becomes more and more concentrated. Therefore, the wastes from desalinization plants consist not of heaps of salt but of brine that is between twice and four times as salty as the original intake water. The plants that may one day distill many millions of gallons a day will need to have their intake and outlet pipes well separated so as to avoid a concentration of brine in the wrong place.

Freezing out the salts from the sea has some advantages over the process of distillation and condensation. For one, the temperature gap to be bridged by the supplied energy is less between ambient and freezing than it is between ambient and boiling temperatures, so that insulation requirements are less for the freezing than for the heating process. Also, oxide scale forms less rapidly at low than at high temperatures and there is less corrosion, making it possible to use cheaper materials. On the other hand, more mechanical energy is required for the freezing process than for the use of heat in desalinization, since not only the water but also the cooling liquid must be moved. Of the freezing plants for fresh-water production that are now

operating in Israel, Japan, and the United States, none is much more than a pilot project, with high unit cost. Experiments with various coolants are under way in many countries, however, and the desalinization of sea water by freezing is likely to become competitive with the much older distillation process if it does not outstrip it in the near future.

The third method of desalinization, known as electrodialysis or the membrane process, divides the salt from the water by means of electricity. The brine is led through narrow channels made of plastic and lined with membranes, and with electric connections so arranged that positive ions such as sodium and calcium migrate through the membrane to seek the negative current source, while negative ions of chlorine (the most important ion in sea water) or of sulfate correspondingly leave the channel along the opposite wall, crossing through the membrane to the positive pole. Leading trickles of salt water through many such channels yields fresh water of variable purity, depending on the rate of flow and the time of treatment and, of course, on the initial salt content of the brine. The process is as yet too expensive for use with undiluted sea water, since the electrical power required varies directly with the number of ions present. The membranes are fragile, and impurities can spoil their surfaces; thus some pretreatment of the water is usually advisable. Electrodialysis is now feasible with brackish water though it is still expensive. Some plants for the purpose exist already, not necessarily by the seaside but situated rather, as are the solar stills, on arid uplands with a natural underground supply of saline water.

Research is under way on processes other than electrodialysis that would use semipermeable membranes akin to those in plant and animal cells. Natural and artificial membranes are being tested, as are the respective physical and chemical properties of the dissolved elements and of the water molecules themselves. The chief of the research division of the Office of

Saline Waters, Department of the Interior, says that processes such as those already described do not supply the ultimate answer, but that it lies in a yet undiscovered process. The best hope for the much-needed low-cost process of desalinization obviously is basic research in relevant areas of the natural sciences.

There are several steam distillation plants, each of which now yields more than a million gallons of water a day while supplying electric power from the heat generated by evaporation. Most of these plants use coal as fuel, but atomic power will come into its own with the development of nuclear power plants. As of 1966 some sea-water desalinization processes were producing fresh water at a total cost of about $1 per thousand gallons at the plant site—that is, at sea level. In the United States the average cost of natural fresh water is less than a quarter of this amount.

Several important economic considerations are to be noted here. First of all, desalinized water becomes cheaper per gallon as plant capacity increases. It is believed that a distillation plant capable of meeting the daily requirements of a few million people—that is, several hundred million gallons a day—could produce fresh water, again at the plant site, at a cost of 30 cents or less per thousand gallons, and thus be competitive with the present average water price from the watershed. Moreover, as the demand for water increases and more costly dams and reservoirs are built, the cost of natural fresh water will go up—as will the cost of fresh water from the sea that is transported for any distance from the desalinization plant. According to present estimates, water costs roughly double with every hundred miles inland and every thousand feet up from the sea. For water that has to be pumped uphill as well as inland, as it would have to be in California, the cost may be increased to four or more times what it was at sea level.

There are regions whose population must rely on desalinization for their water supply and where the cost of the process need not be competitive with other sources. These include Kuwait, Aden on the Red Sea, certain parts of Texas, and the arid coast of Northern Australia. In Baja California, there are plans for a dual-purpose plant to be built jointly by the United States and Mexico, that will provide urgently needed fresh water from the sea together with atomic power. Here, desalinization will mean the difference between barrenness and regional prosperity. The price of water is once again of secondary concern, though the coupling of desalinization with the re-use of the water in domestic circulation would be an advantage.

Today domestic water supplies and sewage treatment plants are separate, and the cost of both processes is borne by the consumer. But since unwanted dissolved and/or suspended solids must be eliminated both from recycled domestic supplies and from saline or brackish water, the treatment could be the same at least part of the way, and substantial savings could be realized. Such an arrangement is already regarded as practical for huge seaboard cities, such as Tokyo, that have outgrown the natural fresh-water supplies around them.

Regions such as the eastern seaboard of North America, which have an ample fresh-water supply but use it badly and recklessly, will probably not rely on desalting of ocean water to any large extent. A possible alternative—proposed by R. D. Gerard of Lamont Geological Observatory—is to build dams across both sea connections of Long Island Sound, thus turning it into a lake that would hold a vast surplus of fresh water, far above the present needs of New York City. Although such proposals are to be considered seriously, the most effective way to overcome the water squeeze upon many urban areas would nevertheless be a cleanup of industrial pollution in rivers and estuaries and immediate re-use of purified sewage—anathema

though this may be in the light of the present attitude toward such matters.

Power from the Sea

Desalinization of sea water is only one of many new energy-demanding endeavors connected with man's increasing mastery over nature and with the rapid increase in human numbers. The geochemist Harrison Brown, who has projected the world's demand for energy in the future, believes that a hundred years from now it will be roughly five times what it is today, and if those who suspect that Dr. Brown has underestimated the future growth of population are correct, the figure will be even higher. Among the many promising schemes for satisfying that demand some would rely upon the land, others upon the sea.

Some engineers have in mind the gigantic forces of the waves and tides, to be used according to principles suggested in Chapter 1. So far, though, most such plans remain no more than that. Although mills and smithies have been driven by the tides for centuries, at only one site, on the estuary of the river Rance on the coast of Brittany in France, has the power of the tides been harnessed on a grand scale. As on the Bay of Fundy (see page 18), the entry of the tides into the estuary of the Rance produces what is known as a tidal bore—a large mass of water that is carried upriver to a height of 20 feet or more and rushes out again with tremendous force. A dam across the Rance houses special turbines, which function by means of a small pressure differential between incoming and outgoing tides that are retained by the dam.

The Rance project called for the building of a gigantic dam and devising low-pressure turbines, as well as for solutions to special problems posed by the site. Virtually abolishing the tidal regime of the river is likely to alter the conditions of the

plants and animals living there. Some may disappear and new species may establish themselves. Such changes would be all the more interesting if a record were kept of every alteration in the environment as a result of human technology—though it does not appear likely that a comparative study of such things will be made.

Although the Rance project is proof that harnessing the tides on a large scale is technically feasible, it has not proved that such a project is economical. In fact, the installations required are so large as to be more expensive than several other ways of producing electricity, including the use of nuclear power. The Rance project, however, satisfying from an engineering standpoint, is considered of marginal value economically and can be defended only when the price of coal in Europe and the cost of transporting it to industrial sites where it is urgently needed are included in the calculation.

Similar objections preclude any serious plan for the construction of thermal power plants as yet another way of extracting energy from the sea. Here, again, even though no fuel is needed, the installations are expensive, as well as delicate and vulnerable to wind and weather. The principle, a simple one, is as follows: On some tropical coasts with a steep drop-off it might be possible to sink a pipe straight down into the deep cold water underlying the warm upper layer. This cold water would be evaporated to produce a stream of low-pressure steam, which would then be used to drive a special kind of turbine. In practice, however, there would be the difficulty of designing low-pressure turbines with the requisite efficiency; the need for gigantic intake tubes, twenty or more feet in diameter, to be sunk into the sea; and the problem of the salt that would accumulate and remain behind as the cold water was vaporized. Nevertheless, French engineers did try to install just such a turbine on the Ivory Coast near Abidjan, probably the most favorable situation anywhere for the

project. On two occasions tropical storms played havoc with the laying of the pipes, and the scheme was finally postponed.

Thought has been given, finally, to harnessing the power of the waves, which after all have the attribute of lifting water particles to a certain height, at which they can be conceived as having a head of potential energy. It might be possible to devise baffles along the shore so as to gather wave-carried water masses into a basin that would be used as an elevated reservoir, again to drive low-pressure turbines. Gadgets that harness the water-lifting action of the swell in the open sea, though, may be worth the consideration only of the writers of science fiction.

The difficulty with wave power is that few shores are especially suitable for harnessing it and that the installations would have much the same shortcomings as those of the previously mentioned devices for solar desalinization on the sea: namely, that they would be delicate, easily put out of commission by the forces of nature, and hard to maintain—as well as that large ocean expanses would necessarily be involved.

Perhaps there may be an occasional tidal power development in the future. Under very special circumstances it might still be possible to use the temperature differential between surface and deeper water, but the development of wave power does not seem at all likely. The chances of using these three sources of energy is all the more remote since the sea contains a much more economical fuel, namely, the heavy isotopes of hydrogen that are locked up in heavy water, the raw material for nuclear fusion reactions. Fission and fusion reactions both liberate tremendous energies in atomic nuclei. Fission relies on the splitting of large, heavy nuclei, such as those of uranium or plutonium, whose atomic weight is more than two hundred times that of hydrogen, the lightest element. Although electric power produced by atomic fission is beginning to be competitive with other sources of electricity, it entails some disadvan-

tages. The raw materials are heavy elements, some of which decompose and turn into smaller units, with many isotopes that give off radiation. According to their potency they must be either buried, locked in concrete, or otherwise disposed of. Methods of binding them permanently in some harmless way have improved, but still the disposal of wastes, notably the low-level wastes from reactor-cooling waters, poses problems in the full development of generators of thermonuclear fission.

Fusion, the second and much more potent source of nuclear power, is used in the hydrogen bomb and is a process continuously occurring in the sun. In it hydrogen and its isotopes—mainly deuterium, having an atomic weight of 2, but also tritium, whose atomic weight is 3 (for ordinary hydrogen it is 1)—react to form helium, the next lightest element after hydrogen. Far more energy is liberated for each fusion than is freed by fission. Fusion, moreover, is a clean reaction, in that there is little production of radioactive isotopes and therefore no contamination of the environment. It would be of advantage to reduce the destructive fusion process to a smaller scale than that of exploding a hydrogen bomb, so as to produce electricity by means of sustained reactions. The one great obstacle here is that the reaction takes place only at almost unimaginable temperatures, which are best engendered in the extreme heat of fission (hence the seeding of hydrogen bombs with an atomic detonator)—a temperature that no metal or other substance can now withstand. Yet there is reason to believe, on the basis of theory and of some very preliminary experiments, that eventually a way might be found for using fusion instead of fission for the peaceful employment of nuclear power. (An interesting sidelight here is that fusion reactors can be much smaller than those used in fission, because the energy yield of the reaction is higher.) Ocean water will eventually come into its own as a source of deuterium inasmuch as more than one in every hundred thousand water molecules contains heavy in-

stead of normal hydrogen. The difference in physical properties between heavy water (D_2O) and normal water (H_2O) means that the former both melts and boils at a higher temperature than the latter. Thus the separation of the two is not difficult, and is already being carried out to stockpile hydrogen bombs.

Minerals from the Sea

Every million gallons of sea water contain a little over a quarter pound of aluminum, along with traces of platinum, gold, and silver, as well as many other elements in varying proportions. With a few notable exceptions, though, these truly watered-down treasures are comparable to plankton, so far as the likelihood of extracting them by any economical process is concerned. There are as yet, and there will be for a long time to come, less rarified sources of these same elements on land, where their extraction and refining takes less energy and is therefore less costly than if they were taken from the sea.

Salt is one of the exceptions, as are bromine and magnesium. Of late uranium has appeared to be yet another. The National Physics Laboratory of Great Britain has developed a method of extracting it from the sea that is potentially competitive with the ways of taking the metal from low-grade, land-based ores.

In most maritime countries, especially those in warm climates, salt has been evaporated from brine from time immemorial. Fortunately, the undesirable impurities settle out of table salt (sodium chloride) before it crystallizes, and can be removed without difficulty from the concentrated brine. But sea salt is now less important economically than that mined from vast subterranean salt deposits, once the location of shallow seas, and it appears that salt is one commodity that will not run short, no matter how large human numbers grow.

Bromine—which at room temperature is an amber-colored, pungent liquid—is likewise plentiful, and aside from being mined or taken from subterranean brine it is being extracted from the oceans in vast amounts. The process consists essentially of binding it with and then liberating it from a series of chemicals by means of evaporation and condensation, during which the brine becomes more concentrated. The element's main use is as ethylenebromide, the antiknock compound in auto gasoline. For a while the S. S. *Ethyl* was one of several ships in use as floating bromine extractors. The practice was given up, however, for much the same reason that harvesting plankton by the same means is impractical: as the intake funnels become larger the ship is obliged to slow down, and since it must void its waste water, there is a probability that the law of diminishing returns would set in as a result of dilution. Land-based extraction plants must be situated where the effluent can be entirely separated from the intake. Like the supply of salt, that of bromine in the sea will outlast the natural supply of petroleum fuel.

Magnesium is another element found both in the sea and in terrestrial deposits. During World War II, when shipping lanes were closed, the process of extracting it from sea water was of greater importance than it is now. The element is refined from the ocean through a series of chemical reactions that render it alternately insoluble and then soluble again, until it can be purified by electrolysis to yield molten metal. Aside from its main use in metal alloys, the annual use of magnesium for medical purposes runs into many tons; nearly 10,000 pounds a year of magnesium-containing antacids and laxatives are used by the thousand-bed hospital at the University of Michigan.

It may well be that many minerals will eventually be extracted directly from the sea, as Harrison Brown suggests in *The Challenge of Man's Future*, but that development is centuries if not millennia away. In the meantime resources on and

under the sea floor, notably petroleum, will be the main challenge to ocean engineers today and for the next few generations to come.

One of the largest rigs for drilling oil now under construction could stand astride London Bridge, and will operate in the North Sea at a depth of 300 feet in tapping buried oil far under the sea floor. In mid-1965 it was but one of nearly fifty such rigs with a capacity to drill in waters down to 600 feet. Those that are placed in shallower water all over the world are counted in the hundreds (Fig. 51).

The commercial production of oil dates back just over a hundred years. Within a single century the mining of liquid fossil fuel has become extensive, and with it man's increasing mastery over distance on land and sea and in the air. Before the nineteenth century was half over serious thought was already being given to the diminishing underground supplies on land. Petroleum geologists had realized, of course, that the continental shelves contained substantial further resources laid down when plant and animal matter from ancient seas was buried under sand and mud and transformed through aeons into crude oil, oil sands, and oil shale, to be drawn upon as soon as the technology was available. Accordingly, there is just as much chance today of finding rich oil deposits under the seas as there originally was of finding them on dry land.

Three methods, all applicable to the sea floor, have been important in the location of oil deposits. The first is seismic exploration, which relies on differences in the composition and structure of an overlying geological layer and the oil stores underneath. When a small charge is exploded on the sea floor, the nature of the echo from it enables a geologist to map the various strata. A second exploration technique relies on the known magnetic characteristics of layers with and outside of oil, and a third measures their effect upon the pull of gravity. Since oil deposits in shallow water often occur below salt

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Fig. 51. Offshore oil-drilling platform near the California coast.

domes with very distinct magnetic and gravitational effects, they can be delimited fairly exactly even though they may lie several thousand feet underneath the sea floor.

Liquid fossil fuels under the continental shelves, including

oil sands, shales, and gas, have been estimated as equivalent to 2,500 billion 42-gallon barrels of oil. According to this estimate, at the present yearly oil consumption of about 10 billion barrels throughout the world, there should be about 250 years' supply buried beneath the sea. It must be assumed, however, that the consumption will increase sharply with the general rise in standards of living, and it should be added that submarine oils are only a part of all fossil fuels. Meanwhile, new subterranean sources are continually being discovered. Though together these several tendencies cancel one another out, there can be no doubt that the total supply is limited and that the human race will eventually run out of fossil fuel, even supposing that it becomes possible to drill from deeper locations than the 1,000-foot contour of the continental slope. The next step might be to place refineries under the sea (Fig. 52). Whether the supply is finally exhausted around the year 3000, as some geologists suggest it may be, or a few hundred years earlier than that, there is no doubt that it will be exhausted sooner or later, since no coal or petroleum is being formed now and since we are using up the present stores at an ever-increasing rate.

Reynolds Metals Company

Fig. 52. Artist's conception of future undersea oil field on continental shelf.

It is not surprising, then, that thought is being given to the artificial production of carbon fuels—which, since crude oil is derived mostly from fossil plants, would rely upon plants as raw material. Special strains of algae that produce a high yield might be grown in shallow ponds, and no doubt sewage and other fertilizers would serve to augment their mass. The algae could be transformed in a number of ways, the most likely of which would employ bacteria as a decomposing agent to produce gases such as methane. Many hydrocarbons, including gasoline, can be synthesized in this way. There are obstacles, though: once again the necessary devices would be vulnerable to the elements, need much space, and be expensive both to build and to maintain. On the other hand, global control of the weather may be in operation by then, so that only the factor of cost would constitute a problem. One may muse, at any rate, that the far future will see transportation devices driven with fuels that come from algae, in cities that either float on the sea entirely or are partly tied to a land base (see the final section of this chapter). We may be certain, however, that burning gasoline for pleasure on Sunday afternoon drives or motorboat rides will no longer be a usual pastime.

In the meantime, while the supply of petroleum lasts there are still other problems to be solved, notably that of ownership. Gigantic sums of money are at stake in the exploration for and exploitation of oil, along with tidy revenues for the individuals, states, or countries whose function it is to lease the rights to that exploitation. In 1945, to avoid a free-for-all and to secure equitable control, President Truman issued a proclamation that "the Government of the United States regards the natural resources of the subsoil and the seabed beneath the high seas but contiguous to the coasts of the United States as appertaining to the United States, subject to its jurisdiction and control." Where the shelf is shared with another state, boundaries were to be determined on equitable principles. Most important, the

waters above the shelf and outside the territorial limits, together with their resources, were to remain free and international.

A similar wording was adopted in 1958, at the Geneva Convention on continental shelf resources, sponsored by the United Nations. The continental shelf was defined at that time as "the seabed and subsoil of submarine areas adjacent to the coast but outside the area of the territorial sea, to a depth of 200 meters or beyond that limit, to where the depth of the superjacent waters admit of the exploitation of the natural resources of the said area." The Convention has now been ratified by twenty-two countries, including the United States.

There was still a need for clarification, for instance, concerning the distinction between living and nonliving natural resources. The law of the sea with regard to its living resources has already been considered; concerning nonliving resources, especially, the clause that speaks of a limit set by a country's capability for exploitation, and potentially extending beyond the 200-meter contour, might in the future give rise to conflicts—as we shall see when we consider the mineral deposits of the deep-sea floor.

So far as petroleum is concerned, however, the convention has laid down ground rules that are equitable and easy to follow, in the provision that shallow seas, such as the area of the North Sea between Northwestern Europe and Great Britain should be subject to boundaries that project from those of the land and bisect the sea midway between the shores. Though Great Britain thus receives the lion's share of the total area, she does not necessarily also gain access to the richest deposits of oil, since the exploration for oil and gas beneath the North Sea was initiated as a result of the discovery of huge inland deposits of natural gas not far from the Dutch coast. The gamble—and all drilling for oil and gas is precisely that, at least to a certain extent—is for particularly high stakes

because of the field's location. Just as offshore oil in Texas, Louisiana, and California is all the more valuable because it occurs close to industrialized shores, in the same way North Sea oil would free Europe, at least in part, from its dependence on Middle Eastern oil, which has to be transported over considerable distances. The gas that is discovered may have yet another and quite unexpected use. From Shell Research Laboratories in Milstead, Kent, in England, comes a report that it is possible to make a colorless, odorless, and tasteless edible protein from methane, the gas that is bubbling from under the North Sea. Since gasoline can be synthesized from methane as well, however, there may be competition over the use to be made of the gas, for as long as the subterranean or submarine supply lasts.

The Dutch, then, own what would seem to be a valuable piece of submarine territory. The actual leasing of it, which might net the government a substantial income, not to speak of profits to the lessee, has been held up temporarily by an ironic circumstance. In the Netherlands, as in other European countries, radio and television are under strict government control, and to escape that control an enterprising Dutch citizen built a sea platform to house a television station beyond the three-mile limit. His telecasts were an immediate success, but the matter was so embarrassing to the government that the military were finally dispatched to shut down the station. There was a violent public outcry against this act of force, the legal basis of which is still in dispute, and as a result the government fell, whereupon a caretaker government temporarily shelved the pending legislation that would have provided for the leasing of government holdings in the North Sea.

Throughout the world offshore petroleum resources occur in geologically distinctive regions, of which the Middle East is the most favorable, followed by the East Indies and the continent of South America. North America is not far behind. Texas

towers will thus soon be found off shores all the way from Abu Dhabi to Zanzibar. And wherever there are such installations conservation-minded people naturally begin asking about oil pollution from submarine drilling. Fortunately, the process itself is quite clean, and once the viscous liquid is set flowing there should be no leaks. If the well is close enough to shore so that a pipeline can be constructed, oil spills are minimized. Farther out at sea the oil eventually goes into tankers, though it may first be stored in large underwater fuel caches of rubber or metal. Clearly there is the possibility of spillage and accidents, as well as the disturbance to the sea floor by the legs of drilling platforms and the driving of pilings for reservoirs. Abandoned wells and discontinued installations also may be sources of pollution. Though attention is given to all these in the Geneva Convention, there remains the question of the enforceability of such conservation regulations as do exist. The areas involved may be infinitesimal as compared to the sea at large, but they are near shore, and thus near human habitation, and they will increase in size. It would be naïve to insist that there must be no disturbance, and thus no exploitation, but unless a wise compromise is reached between minimum interference and maximum use or profit there is a real risk that the last and largest frontier on earth will be despoiled.

Dredging the Sea Floor

Any compromise based on minimum interference becomes impossible where minerals are dredged from the sea floor. In that process part or all of the sediments are removed, stripped of their valuable content, and then dumped. However, if an area thus mined is not disturbed again, it can recover its complement of sea life within a reasonable length of time.

The rise of ocean water levels since the last glacial period was at its height has covered many shallow beach terraces and

beaches where alluvial deposits of minerals are as likely to be found as on high ground. Alaskan rivers were once subjected to a gold rush, and now the gold-bearing sands underneath the sea's surface, off Nome and Juneau, are soon to be mined. Tin-bearing ores in Malaya, Thailand, and Indonesia dip underneath the ocean and are dredged up from depths of a hundred feet or more. Even diamonds are recovered from the gravel of the sea bottom off the southwest coast of South Africa.

In South Africa the search for diamonds originally proceeded by sifting the sand and pebbles of certain desert valleys where the rough gems had been left after the lava that originally contained them had weathered and been washed away. Similar formations extending out into the sea are now successfully combed for diamonds. In fact their gem yield per ton is now five times that on land, where the best sites have already been sifted once or twice.

The diamond prospectors of the hydrosphere had to proceed without the advantage of being able to mark, triangulate, and pinpoint a site, as on land; instead, they had to operate from an unmarked and ever-moving surface, though the task of position finding was eased by the proximity of the deposits to the shore. Underwater diamond mining takes place in anywhere from 40 to 200 feet of water. With the establishment of electronic direction indicators equipped with beacons, the position of dredging barges can be controlled within a margin for error of about three feet.

Raising the gravel aboard a ship in order to sift out the diamonds—sometimes in the 30-foot swells that prevail on the coast north of Capetown—can be accomplished either by an air-lift pump, which releases a stream of air bubbles into the mouth of a flexible hose so as to draw both water and gravel upward, or by a simple water suction pump, operating on the principle of a powerful vacuum cleaner. The pumping force must suffice to raise pebbles with a diameter of ± one half inch,

a size close to that of the largest diamonds that are to be expected. Whatever Kohinoors remain on the ocean floor must stay there to adorn the mermaids. Once aboard, the gravel is screened and sorted as in land mining. The diamonds are separated from the lighter pebbles by placing the gravel in a heavy liquid, into which the gems sink while the gravel rises; the tailings are then dumped overboard. The determining of exact positions and careful navigation become very important at this stage, to avoid going over the same ground twice.

The Marine Diamond Corporation of Capetown put its first mining barge—what is referred to as a floating diamond mine—into operation in August, 1962. Underwater prospecting had been reasonably promising, but there was still a gamble before a full-fledged commercial enterprise recovered its high initial outlay. The barge had been dredging in diamond-bearing gravel for just under a year when it was caught in a storm and shipwrecked. But meanwhile it had raised 51,000 carats of rough diamonds of gem quality. De Beers Consolidated Mines Limited, the world's largest diamond producer, then became interested and bought the participation rights in Marine Diamond's underwater lease. Now several mining vessels are sucking gravel from the sea floor of the region.

Diamonds make up but a minute fraction of the dredged gravel that is raised for sifting. If there were an attempt to recover the manganese and phosphorite deposits on the deep-sea floor, on the other hand, all the dredgings would be retained for extraction of the minerals. Because they cover such large areas of the deep-sea floor, the holding of a position at sea would be far less of a problem than it is for submarine diamond mining. The task of raising the deposits, however, would be far more difficult than for the gems, since the deposits lie at depths of from several to many thousands of feet.

Dredges could be designed that would raise and empty into the deposits barges, but in depths of less than a thousand feet

they would already have become inefficient because of the time lost in raising and lowering them, quite aside from the energy required for emptying. Minerals that lie on the sea floor will most likely be raised by suction, as gravel is in the mining of diamonds. A rotary suction head with a large hose that sweeps the sea floor at from 15,000 to 20,000 feet and that is monitored by a television camera submerged nearby would seem to be the most sensible device yet proposed. A huge undersea tractor, moving on caterpillar treads, that would house dredging and metal-purifying assemblies also has progressed at least from the engineer's doodling pad to the drawing board. The step from the existing shallow-water diamond sweepers to such abyssal dredges, of whatever design, may prove more difficult in practice than in theory.

Among the minerals to be aimed for by such dredging mechanisms are the phosphorites that occur on many parts of the ocean floor, including vast areas off both east and west coasts of North America. These phosphorites could be used as fertilizers almost as they are, so that there would be little need for elaborate refining. Manganese nodules are still another deposit, lying generally much deeper than the phosphorites (Fig. 53). The floor of the Pacific, for instance, is covered in many places with metallic accretions that contain copper, nickel, molybdenum, and other metals aside from manganese and that occur in densities of several pounds to the square foot. Moreover, in contrast to the ores that are currently mined from the earth's mountains and that dwindle as they are exploited, many such deep-sea minerals are forming continuously, setting out as colloidal particles and slowly growing into granules and then into nodules by virtue of their electrochemical properties. Indeed, the continuous formation of manganese nodules on millions of square miles of the Pacific sea floor is estimated at 10 million tons a year.

Economically, deep-sea mining appears promising. Dr. John

Science

Fig. 53. Thin section of a manganese nodule from the floor of the Indian Ocean. The long diameter of this section is 62 mm ($2\frac{7}{16}$ inches); it is clearly shown that these nodules grow by addition of thin layers of material from the surrounding water. (Reprinted courtesy of Dr. Raymond C. Gutschick and *Science*.)

L. Mero, a leading American authority on the subject, believes that manganese, nickel, cobalt, and perhaps copper will eventually be more cheaply taken from the sea than from the land, especially as the respective mines on land become gradually depleted. Other experts, like K. O. Emery of the Woods Hole Oceanographic Institution, are less optimistic. International competition for such deep-sea mineral resources may not be a serious problem, since the deposits are vast and the nations with the technology capable of exploiting them are few. The Truman Proclamation, its intent ratified by many nations, extends a country's domain over the sea floor as far as her capabilities for exploitation permit her to go—which is certainly beyond the shelf. It presents a good basis for negotiations between individual states if need were to arise, as when two nations wished to exploit the same areas.

Another line of speculation concerns the site at which these minerals would be separated and refined; should it be at sea or in land-based factories? Floating underwater stations which would be protected from wind and wave action have been suggested. If they were less than a hundred feet below their connections with the surface craft, such stations would be manageable, and if there are to be floating cities as a future escape from population pressure on land, some of these might be directly associated with mining operations on the sea floor.

Cities to Come

Large cities threaten to grow larger still, and the land between Boston and Washington will soon be a continuous paved metropolis of more than fifty million people. But cities will have to change in the future if the men who build them are also to survive in them. City dwellers must then do with

less water than they now use, and to have breathable air and relieve congestion they may have to forgo automobiles. The central districts and the nearby suburbs will need to be run on electricity, to minimize air pollution. City dwellers then as now will floek on hot Sundays to the few unpolluted beaches and gaze out on the shimmering blue waves. Since there is space on the sea and the air is without fumes, why not live there?

The main reason that there has been no colonization of the sea is simply that there was no urgent need to do so, but if there had been, the weather would certainly have constituted an obstacle. In Florida, for instance, the insurance premium on a vessel is ten times that of a house of equal value, and every year, despite radio communication and searches from the air, two or three dozen commercial vessels still disappear without a trace. Furthermore, houseboats, clearly the forerunners of ocean settlement, are found only in the most protected salt-water locations.

Another obstacle would have been the lack of adequate technology. Very recently, however, the development of plastics and of such inventions as the hydrofoil and hovercraft, of seagoing rigs for drilling and mining, and most important of all, of the underwater dwellings that have already been described, the possibility of ocean settlements has been serously considered. What are the chances that these will come into being?

Some of their proponents, including Dr. Richard L. Meier of the University of Michigan, suggest that floating cities will be a development by the twenty-first century. They argue that cities will simply have run out of space on land for the building of suburbs. Indeed, the coastal cities of Japan, lying in a narrow strip of land between the mountains and the sea, are already experiencing this squeeze to a degree that it may be asked why suburban houseboat communities (with sea wall

protection) are not more prevalent.* Meier and other planners envisage a transition to cities on the sea through temporary and then permanent houseboat settlements, which are most likely to arise in tropical and subtropical climates.

Such communities, which might be an outgrowth of seafront subdivisions or luxury marinas, would differ from the clusters of junks that dot the harbors of Hong Kong and Singapore. The junks are the abodes of the poor, whereas the houseboat communities envisioned here would permit the well-to-do to escape the city. Vendors would come by in boats, as they do in Bangkok or Venice, with food, fuel, luxuries, and perhaps water—which, on the other hand, might be a piped-in commodity. Wastes would be collected in the same way. Since water littered with floating rubbish can be more unsightly than littered ground, it would be hoped that the owners of houseboats would set great store by a clean environment.

In order to constitute a community, as distinguished from a camp, there must be permanence, together with such services as schools, police, and utilities. A service of the greatest importance to floating communities would be protection from storms. This might be afforded by the ambitious project of a high-rising sea wall, so constructed as to turn the destructive swell into innocuous surf and to deflect the wind upward, in the same way that a shelter belt of trees on the prairies protects the farm in its lee. Or, it might be simply an evacuation service for the few days a year when the winds were most violent. Those days might be spent on land, or in an underwater shelter, at a depth, say, of from 30 to 50 feet, where the force of the waves

* *Esquire* magazine for July, 1966, tells of plans for a floating hemisphere for weekend use, complete with a self-contained underwater observation chamber that extracts oxygen from sea water. Although certain practical difficulties—such as the possible fouling of the underwater chamber's artificial gills—are not mentioned, the idea is not altogether beyond realization even within a few years.

would be reduced but where pressure problems would be manageable. For the latter the U.S. Naval Laboratory's Floating Ocean Research and Development Station, which has an enclosed space that can be lowered beneath the waves, to remain submerged and self-sufficient for several days, may point the way.

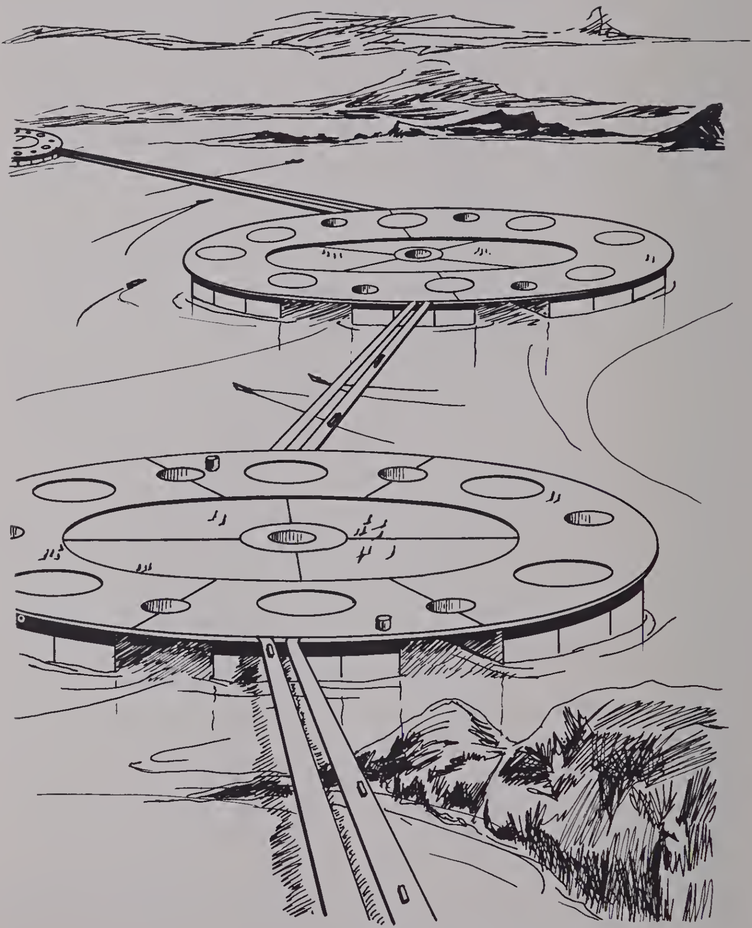
Such installations are expensive, however, and are probably beyond the reach of cities such as Calcutta or Djakarta, where ocean suburbs would help relieve the intense pressure of overpopulation. It may be surmised that floating suburbs located a few miles out at sea and thus somewhat self-sufficient will have to await a time when hurricanes and typhoons can be diverted, if not prevented from forming altogether. Attempts to deal in some way with cyclonic storms will certainly be made, and some meteorologists give priority to the hope of modifying the weather.

Although there may be pressure to use the sea as living space, and although there is already the technological skill for using plastics to build sea-based single dwellings or apartment houses, and for solving all the problems of transportation within, to, and from such settlements, nevertheless, it is hard to imagine that sea cities could ever become wholly self-sufficient. Those devoted, for example, to recreation or education would not be likely to grow into true cities, nor would they need to provide sea-based jobs for their temporary residents. The industries for lifting manganese nodules from the sea floor would need to be highly automated, so as to require few workers, and the processes of refining and working the metal need not, after all, be based at sea. It may be possible to raise a substantial tonnage of fish on the algae used to purify and convert such a city's organic wastes. Its residents might engage in still other kinds of mariculture, such as growing plants and animals in huge plastic trays, floating and coupled together in such a fashion that they could be rolled up like a carpet whenever the city had to

be moved—because of bad weather, for example. Dr. Meier suggests that certain special products might be manufactured at sea, in shops or small factories that would be related to the maintenance and functioning of the community—such as fittings for houseboats and other sorts of marine equipment. Perhaps the inhabitants of sea cities would be older people, either supported by the government or independently wealthy. Artists and writers, as members of society who need no industrial machinery to discharge their function, might be at home in floating cities. There are flaws in all these suggestions, and no doubt others will be spelled out by the floating-city planners. If there are no means to overcome the dependence of such communities upon shore-based cities, they can become neither large nor truly self-sufficient. Yet the fact remains that living space on land will be at a premium near many shores long before human numbers can have become stabilized. And no doubt some adventurous spirits will become the pioneers of a new way of life at sea.

Some planners optimistically speculate that floating cities of 50,000 or more could be held together while they move about, very slowly, so as to take advantage of the most desirable climate at all seasons. They would be designed to mimic a Pacific atoll, with one or two sets of wave-breakers far beyond the enclosure of the city proper. The whole construction would be several miles in diameter, with much intervening water and a thorough water separation of industrial and residential areas (Fig. 54). There might be overhead monorails or hydrofoil boats for rapid transit; slower water craft would cover shorter distances. The dwellings would undoubtedly extend downward beneath the waves. It is possible to imagine a bar forty feet or more below the surface, where a large picture window would afford a view onto a transplanted coral reef.

Long before floating cities can begin to be a reality men will have become far better acquainted than now with life at and



Freely redrawn after Kiyonori Kikutake of Japan

Fig. 54. Future city on the sea.

beneath the surface of the ocean. At present an explorer of the sea may be likened to the American settlers who struck out for the unknown beyond the western frontier. There is one important difference, however; our forebears conquered the land in ignorance of their interactions with other living things and with the soil; they plowed where they should not have done so and cut trees that ought to have been left standing. They were unaware of ecology, the science of the interaction of plants and animals with one another and with their surroundings.

Today marine ecology and other areas of oceanography may help us to envisage at least some of the consequences of our actions in the sea before we embark upon such actions. Men have changed the face of the earth; through hindsight they have come to be distressed by what they have done. Men are now about to change portions of the sea floor, and perhaps the face of the sea as well. They must make those changes with their eyes open, aware of possible consequences and of human values. Nor is the individual conscience enough. Its dictates must be expressed in action and in plans and ordinances, based on an understanding of man's interaction with the sea.

Those who try to learn from previous mistakes will be aware of the lack of respect shown by Americans toward the land. Though portions of it were finally set aside to be enjoyed for their beauty, the rest bears the ugly marks of lack of foresight or of any thinking according to ecological concepts. Institutions for managing the environment were each concerned with some special purpose, such as flood control, road building, or irrigation, and their organization did not encourage anything resembling an ecological point of view.

At the time no popular understanding of the interdependencies in the environment could have been expected, since the greatest obstacle to such holistic thinking is in the culture itself. That obstacle, incidentally, is just as prevalent in Soviet Russia as in the United States, though both nations are great

believers in technological progress. Lynton Caldwell of Indiana University, writing in *Bioscene* on "Problems of Applied Ecology," remarks, "In societies of advanced technology, compartmentalized specialization and an uncritical faith in the beneficence of unguided technology have seriously distorted perceptions of environmental realities." Professor Caldwell sees a continued lack of public awareness of ecological principles and warns that, as both populations and technologies grow at an accelerated pace, piecemeal management can now lead to environmental deterioration more rapidly than before.

The outlook concerning the sea is not entirely black, however. On the international scene United States and Soviet Russian fishery scientists meet regularly to deal with matters common to them both, such as the fish stocks in the western North Atlantic. They exchange research personnel and work on each other's vessels. Thus they get to know each other's special problems and some of the proposed solutions and they agree with one another more often than not. Nationally, there has also been increased awareness, lately, of the unity of the sea; one example of it was the formation by the U.S. Department of Commerce of the Environmental Sciences Services Administration (ESSA), comprising the Weather Bureau, the Coast and Geodetic Survey, the Central Radio Propagation Laboratory, and a newly established institute in the Department to deal with some aspects of oceanography. Broader still is the scope of the National Council on Marine Resources and Engineering Development and a joint Commission of government officials and citizens of the same name. On the executive level, they bridge the gaps between the various government departments and between these departments and industry. The Council is chaired by Vice President Humphrey and has as members secretaries of government departments such as the Navy, Interior, Commerce, Health, Education and Welfare, and others concerned with the sea and its uses, as well as observers from quarters like the Office of Science and Tech-

nology, the Smithsonian Institution, and the Agency for International Development, which are also interested in the uses of the sea.

The Council was created by the Marine Resources and Engineering Development Act (P.L. 89-454) and charged with assisting the President to develop a comprehensive, long-range, and coordinated national program in marine science. Its statutory responsibilities, aside from its advisory function in policy planning, include the coordination of the marine science program of eleven Federal agencies. After it has discharged its advisory responsibilities the Council, which is not an operating agency, will be dissolved. One may suspect, however, that the program it will develop to further marine sciences and technology will include a versatile coordinating mechanism.

That such a mechanism will be needed is clear when one examines only a selected few of the nine priority programs recommended by the Council for early implementation. International cooperation is to be fostered for promoting the peaceful use of the oceans and the foundation of so-called Sea Grant Colleges, which was established by another Public Law somewhat before the Council's creation, should be implemented immediately. The Sea Grant College idea parallels that which made the U.S. Land Grant Colleges such a powerful force in the development of agriculture and will focus on the needs to bring applied science and engineering approaches to ocean resources. Also, weather prediction based on oceanography and meteorology is to be strengthened and, as already mentioned, the Chesapeake Bay model study is to lead to a speed-up in the program to curb estuarine and near-shore pollution. Furthermore, a "food from the sea" program is now to stress specifically overseas demonstration projects utilizing fish protein concentrate.

It is important, when one presses technology into the service of exploiting living, renewable resources, as is the case with taking fish for making FPC, to remember one crucial fact: Tools

of great sophistication and vast power permit Western man to bring about changes in his surroundings at rates far beyond those which operate in the "natural" environment. However, the organisms he exploits, and with which he inescapably shares the planet, live fully in the time frame of organic evolution and are not subject to the same acceleration of events in their lives as he is: If they experience such a speed-up—thermal pollution is a good example—often their only possible reaction is to die.

Thus the human environment will come ever more under our control while we try to cope with the oceans, a part of nature which we know less well than the land, our home. This "running at one speed" as it were, while watching events around us go on at another, will create tensions and malfunctions in society and the environment that may in part be overcome by the good will and the national and international cooperation of men with varied jobs, interests, and knowledge. But the promises for the betterment of mankind that lie in the sea are likely to be turned into true and lasting achievements only when each of us has developed an ecological conscience.

Whether or not we can repair the damages we have wrought by acquiescing, in part through ignorance, to leave behind as scars and as evil-smelling sores abandoned mines and denuded hillsides, polluted lakes and rivers we cannot tell. The knowledge and awareness of what we do to our surroundings will surely help to repair the damages as we face the omissions and commissions of living in a society that must have obsolescence of industrial products to survive. Perhaps we ought to pause, as we stand in the edge of the sea, ready to conquer it in a new and intensified manner. Proposed expenditures for ocean science and engineering certainly herald this quest; gathering knowledge about man's interaction with the sea, and truly beginning to understand it, should help us guard against the kind of mistakes we made on land. It is hoped that this book may make some contribution to that end.

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JOHN BARDACH, Professor at the School of Natural Resources, University of Michigan, is a leading specialist in the field of marine biology. Educated in Europe and North America, Dr. Bardach has conducted significant and original research into the matter of today's water problems, especially as they relate to man.

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